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Accidents and Unscheduled Events Associated with Non-Nuclear Energy Resources and Technology

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Accidents and unscheduled events associated with non-nuclear energy resources and technology are identified for each step in the energy cycle. Both natural and anthropogenic causes of accidents or unscheduled events are considered. Data concerning these accidents are summarized. Estimates of frequency and severity are presented for all accidents. The energy systems discussed are coal, oil, natural gas, LNG, hydroelectric, geothermal, and oil shale., and Solar energy.

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SECTION 1.0

INTRODUCTION

Since the Arab oil embargo, methods of achieving energy independence have received much attention in the United States. Most of the discussion has concerned availability of various energy resources, availability and cost of technology, and environmental effects.

Nuclear energy could supply a significant part of our electrical energy needs. Safety considerations, however, have proven to be a major impediment to development of nuclear energy.

In order to choose intelligently among the alternatives available to us, the safety of using our non-nuclear energy resources must be considered. Although some hazards such as oil spills and coal mine explosions have received significant attention from the public and the regulatory agencies, no comprehensive assessment of the safety of developing our non-nuclear resources has been prepared.

The first step in the assessment of the hazards of non-nuclear systems is a compilation of existing accident data. The purpose of this report is to summarize the available information on non-nuclear power systems. All accidents or unscheduled events, whether natural or man-made, are considered. However, emphasis is placed on major accidents or minor accidents which have a cumulative major effect.

The energy systems covered by this report are coal, crude oil, natural gas, liquefied natural gas (LNG), hydroelectric, oil shale, geothermal, and solar. For the purposes of this report, an accident or unscheduled event is an unexpected incident which poses a threat to human health or safety, plant, property, and equipment, or the environment. These incidents can occur during the construction, operation, or maintenance of the system. Accidents are considered to be incidents which occur because of factors inherent in the individual energy system (e.g., roof collapse of coal mines). Unscheduled events are incidents which may affect more than one energy system and are caused by factors external to these systems (e.g., war, earthquakes). Excluded from consideration are environmental effects or threats to human health, safety, or property resulting from normal operations, whether continuous or batch (e.g., SO_x and NO_x emissions from power plants or water pollution from wastewater treatment systems at oil refineries). Also excluded are uncontrolled discharges to the environment such as surface runoff, acid mine drainage, and fugitive emissions. Because only non-nuclear energy systems are being considered, accidents associated with the development of geothermal resources using nuclear explosives (Operation Gas Buggy) are not included. Supply interruptions also are not considered to be within the scope of this study.

In order to identify accidents which might occur, each resource system was divided into energy cycle elements of exploration, extraction, processing, transportation (including transmission and distribution), and end use. Technologies used in each element were examined for their accident potential and a preliminary list of types of accidents was prepared. This list was then modified based on telephone contact with governmental agencies, trade associations, unions, insurance companies, and other groups with expertise in the field. A list of the organizations contacted is contained in Appendix I. These organizations also were asked to supply data concerning the frequency and severity of each accident.

Table 1 identifies representative accidents or unscheduled events. It is believed that this table contains all major accidents likely to occur, all minor accidents which cumulatively have a major effect, and a sampling of other accidents which might ojcur. This table is not to be considered as exhaustive because it is impossible to envision or to list all accidents which might occur.

The table also contains an estimate of the frequency and severity of each accident listed. The following definitions were used in preparing the table;

Major - Having the potential for causing death or severe injury to more than 10 people, causing more than $500,000 damage to plant, property, or equipment, or having significant ecological impact (i.e., causing severe ecosystem disruption or killing a significant portion of a segment of the local biological community).

Minor or Unknown - All other known accidental or unscheduled occurrences and unscheduled occurrences whose magnitude cannot be estimated.

Frequent - An accident or unscheduled event which occurs at least 5 times in the United States during a single year.

Infrequent - An accident or unscheduled event which occurs 4 times or less in the United States during a single year.

Hypothetical - An accident or unscheduled event which may be expected to occur but whose frequency cannot be estimated because there is no sound basis for objective estimation.

The definition of major accidents should not be interpreted as meaning that accidents with the potential for killing of severely injuring fewer than 10 persons are inconsequential. The death of even a single individual represents an immeasurable and irreplaceable loss. Rather, the purpose of differentiating between major and minor accidents is to distinguish between potentially catastrophic occurrences such as hydroelectric dam failure and less severe individual accidents such as slips, falls, or most automobile accidents.

In most instances, estimates of frequency and severity were based on data presented in the report. For developing technologies, however, data were not

TABLE 1. REPRESENTATIVE ACCIDENTS AND UNSCHEDULED EVENTS ASSOCIATED WITH NON-NUCLEAR ENERGY RESOURCES AND TECHNOLOGY

RESOURCE	ENERGY CYCLE ELEMENT	TECHNOLOGY AREA	ACCIDENT	SEVERITY Major	SEVERITY Minor	FREQUENCY OF OCCURRENCE Frequent	FREQUENCY OF OCCURRENCE Infrequent	FREQUENCY OF OCCURRENCE Hypothetical	REMARKS
COAL	Exploration	Detailed site inspections, including collection of surface and sub-surface strata for analysis and evaluation	Aircraft accident during aerial survey		x		x		Generic hazard
			Personnel injury and/or property damage from improper use of explosives (e.g., detonations, flying debris)		x		x		Generic hazard
			Improper use of boring/drilling equipment		x		x		Generic hazard
			Explosion, release of toxic gases caused by drilling operation intersecting existing natural gas reservoir		x		x		
	Extraction/ Reclamation	Underground	Heavy equipment accidents during initial excavation, site preparation		x		x		
			Explosion and/or fire from fracturing activities		x		x		

(continued)

TABLE 1 (continued)

RESOURCE	ENERGY CYCLE ELEMENT	TECHNOLOGY AREA	ACCIDENT	SEVERITY		FREQUENCY OF OCCURRENCE			REMARKS
				Major	Minor	Frequent	Infrequent	Hypothetical	
	Extraction/ Reclamation (continued)	Underground (continued)	Roof collapse	x		x			Face, roof, and rib falls, although affecting a small number of individuals per occurrence, happen so frequently that the cumulative impact is the greatest underground mining hazard
			Face and rib falls	x		x			
			Bursts (pressure)		x		x		
			Mishandling material, tools, machinery	x		x			
			Electrocution, electric arc burns		x		x		
			Gas or dust explosions	x			x		Gas or dust explosions, although often severe, occur infrequently.
			Haulage accidents	x		x			Haulage or heavy equipment related accidents are second most severe in underground mining activities
			Intersection with existing oil or gas well or reservoir		x		x		
		Surface	Highwall collapse	x		x			Fall of highwalls or slides produces substantial numbers of non-fatal injuries

(continued)

TABLE 1 (continued)

RESOURCE	ENERGY CYCLE ELEMENT	TECHNOLOGY AREA	ACCIDENT	SEVERITY Major	SEVERITY Minor	FREQUENCY OF OCCURRENCE Frequent	FREQUENCY OF OCCURRENCE Infrequent	FREQUENCY OF OCCURRENCE Hypothetical	REMARKS
	Extraction/ Reclamation (continued)	Surface (continued)	Heavy equipment, haulage accidents	x		x			Heavy equipment operation has significant potential for accidents
			Improper use of explosives		x		x		
			Electrocution		x		x		
			Mishandling of hand tools or machinery		x	x			
			Fires		x		x		
			People falling		x	x			
		Auger	Heavy equipment accidents		x		x		Generic hazard
		Spoils disposal	Tailing dam collapse		x		x		Tailing dam collapse can be catastrophic
			Fires or explosions		x	x			
			Landslides, highwall collapse		x	x			Landslides, wall collapse are frequent but often minor
		Reclamation	Accidents involving heavy equipment		x	x			
	Processing	Beneficiation/ Preparation (crushing, sizing, cleaning, drying, etc.)	Fire or explosion from mechanical friction or impact	x			x		Human fatality hazard small, but non-fatal injuries can be significant

(continued)

TABLE 1 (continued)

RESOURCE	ENERGY CYCLE ELEMENT	TECHNOLOGY AREA	ACCIDENT	SEVERITY Major	SEVERITY Minor	FREQUENCY OF OCCURRENCE Frequent	FREQUENCY OF OCCURRENCE Infrequent	FREQUENCY OF OCCURRENCE Hypothetical	REMARKS
	Processing (continued)	Beneficiation/ Preparation (crushing, sizing, cleaning, drying, etc.) (continued)	Ignition of coal dust fires due to local temperature buildup		x		x		
			Accidental release of accumulated dust or fires to the environment		x		x		
			Haulage accidents		x	x			Haulage, conveyor accidents are common
			Mishandling of hand tools or equipment		x	x			
			Gas or dust explosions	x			x		Gas or dust explosions appear to be the two most significant hazards resulting in the greatest number man-days lost per occurrence
			People falling		x	x			
		Liquefaction	Fires, gas or dust explosion from feedstock handling	x			x		Few operating data exist for liquefaction, gasification, or in situ gasification. Therefore, the frequency of most accidents is categorized as hypothetical.
			Pressurized reaction vessel rupture	x				x	
			Explosion due to slurry devolitization, depressurization.	x				x	
			Release of reactants, catalysts, by-products during explosion	x				x	

(continued)

TABLE 1 (continued)

RESOURCE	ENERGY CYCLE ELEMENT	TECHNOLOGY AREA	ACCIDENT	SEVERITY Major/Minor	FREQUENCY OF OCCURRENCE Frequent	Infrequent	Hypothetical	REMARKS
	Processing (continued)	Gasification	Fires, gas or dust explosions from feedstock handling	x		x		
			Pressurized reaction vessel rupture	x			x	
			Explosion or ignition of hot aromatic by-product oils	x			x	
			Release of reactants to environment	x			x	
		In-situ gasification	Uncontrolled combustion of coal seam	x	x			
			Land subsidence	x	x			
			Induced seismicity	x			x	
			Leakage of reaction gases to surrounding strata	x	x			
			Uncontrolled fracturing of coal seam	x		x		
			Accidental disruption of ground water, aquifers	x		x		Available information indicates that methods to mitigate or remove known problems appear insufficient at this time.

(continued)

TABLE 1 (continued)

RESOURCE	ENERGY CYCLE ELEMENT	TECHNOLOGY AREA	ACCIDENT	SEVERITY		FREQUENCY OF OCCURRENCE			REMARKS
				Major	Minor	Frequent	Infrequent	Hypothetical	
		Coking	Normal industrial hazards associated with heavy equipment, or high temperature environment		x		x		
			Explosions during heat-up or battery oven reversals	x			x		Explosions have occurred, but infrequently
	Transportation and distribution	In-mine transportation	Haulage accidents	x		x			
			Conveyor fires, explosion		x	x			In-mine haulage accident causes substantial loss of lives and production
			Fires, explosions during transfer		x	x			
		Surface distribution	Vehicular accidents		x		x		
			Freight transfer accidents		x		x		Generic hazard; coal specific data are not available
			Barge, vessel overturning, sinking	x			x		
			Railway, truck collisions	x			x		

(continued)

TABLE 1 (continued)

RESOURCE	ENERGY CYCLE ELEMENT	TECHNOLOGY AREA	ACCIDENT	SEVERITY Major	SEVERITY Minor	FREQUENCY OF OCCURRENCE Frequent	FREQUENCY OF OCCURRENCE Infrequent	FREQUENCY OF OCCURRENCE Hypothetical	REMARKS
Crude Oil	Exploration	Surveys	Accidents resulting from the use of explosives		x		x		Most explosions are contained
			Accidents on land or ship resulting from handling of equipment		x		x		
		Exploratory Drilling	Blowouts causing gas leaks, oil spills, fires and explosions	x			x		
			Collision of a vessel with a drilling rig	x			x		
			Rig accidents		x	x			
	Extraction (Production)	Well Completion	Blowouts causing gas leaks, oil spills, fires and explosions	x			x		
			Oil spills from causes other than blowouts	x		x			Small spills are frequent; large spills are infrequent
			Rig accidents		x	x			
			Subsidence	x			x		

(continued)

TABLE 1 (continued)

RESOURCE	ENERGY CYCLE ELEMENT	TECHNOLOGY AREA	ACCIDENT	SEVERITY Major	SEVERITY Minor	FREQUENCY OF OCCURRENCE Frequent	FREQUENCY OF OCCURRENCE Infrequent	FREQUENCY OF OCCURRENCE Hypothetical	REMARKS
Crude Oil	Extraction (Production)	Field Processing	Fires and explosions	x			x		
			Spills of brines or emulsified oil		x	x			
			Processing platform accidents involving explosion, fires, capsizing, etc.	x			x		
		Improved Recovery	Subsidence	x			x		
			Steam injection accidents		x		x		
	Processing	Refining	Fires and explosions	x			x		
			Oil spills	x			x		
			Failure of waste-water treatment equipment		x		x	x	Diversion to holding ponds generally prevents release of untreated materials to the environment.
	Transportation and Storage of Crude and Refined Product	Tankers and Barges	Oils spills due to collisions, capsizing, running aground and other causes	x			x		Most occurrences are minor
			Spills and leaks during lightering bilge wash, etc.	x		x			

(continued)

TABLE 1 (continued)

RESOURCE	ENERGY CYCLE ELEMENT	TECHNOLOGY AREA	ACCIDENT	SEVERITY		FREQUENCY OF OCCURRENCE			REMARKS
				Major	Minor	Frequent	Infrequent	Hypothetical	
Crude Oil	Transportation and Storage of Crude and Refined Product	Pipelines	Oil spills due to pipeline failures, valve malfunction, transfer hose rupture and other causes	x			x		
			Fires and explosions	x			x		
		Trucks	Truck accidents resulting in fires and explosions		x	x			Although major accidents can occur most are minor
		Railroad Tank Cars	Derailment or collisions resulting in fire, explosions, or environmental damage						
			Spills and leaks during transfer operations		x		x		
		Tank Farms	Fires and explosions	x			x		
			Tank rupture or overflow		x		x		Although major accidents can occur most are minor
Natural Gas	Exploration	Surveys	Accidents involving misuse of explosives		x		x		Not directly associated with natural gas properties
			Accidents involving radioactive sensors		x		x		Not directly associated with natural gas properties

(continued)

TABLE 1 (continued)

RESOURCE	ENERGY CYCLE ELEMENT	TECHNOLOGY AREA	ACCIDENT	SEVERITY Major/Minor		FREQUENCY OF OCCURRENCE Frequent	Infrequent	Hypothetical	REMARKS
				Major	Minor				
Natural Gas	Exploration	Exploratory Drilling	Blowouts	x			x		
	Extraction	Well completion	Blowouts	x			x		
		Production	Fires and explosions	x			x		Results from uncontrolled release of gas; possible failure of downhole valve, maintenance error.
			Oil spills		x		x		
	Processing	Processing	Release of sulfur compounds H_2S, SO_2	x			x		
			Fires and explosions	x			x		
			Rupture of processing equipment		x		x		
	Transportation and Storage	Pipelines	Leaks, ruptures, explosions, material failures corrosions 2nd party equipment	x			x		
		Underground Storage	Fires, explosions, contamination of water supplies, leaks	x			x		
		Storage Tanks	Leaks, ruptures, fires, explosions	x			x		
		Peak Shaving Plants	Ruptures, fires, explosions	x			x		
		Local Distribution	Ruptures, leaks resulting in fires and explosions	x			x		

(continued)

TABLE 1 (continued)

RESOURCE	ENERGY CYCLE ELEMENT	TECHNOLOGY AREA	ACCIDENT	SEVERITY		FREQUENCY OF OCCURRENCE			REMARKS
				Major	Minor	Frequent	Infrequent	Hypothetical	
LNG	Exploration	See Natural Gas							
	Extraction	See Natural Gas							
	Processing	Pretreatment	See Natural Gas						
		Liquefaction	Fires and explosions	x				x	
			Solids blocking pipeline		x			x	
			Release of refrigerants		x			x	
	Transportation and storage	Tankers	Onboard malfunctions causing spills and fires	x				x	This includes vessel failures not related to LNG but which could affect LNG tanks
			Impact with 2nd body	x				x	This includes rammings, groundings, and collisions
		Transfer	Leaks and rupture of pipeline		x			x	
		Storage and regasification	Structural failures or rupture of holding facilities, "roll-over"	x			x		Only accidents concerning LNG to date involve storage facilities
			Accidents during maintenance	x			x		
			Leakage in regasification lines		x			x	

(continued)

TABLE 1 (continued)

RESOURCE	ENERGY CYCLE ELEMENT	TECHNOLOGY AREA	ACCIDENT	SEVERITY Major	SEVERITY Minor	FREQUENCY OF OCCURRENCE Frequent	FREQUENCY OF OCCURRENCE Infrequent	FREQUENCY OF OCCURRENCE Hypothetical	REMARKS
Hydroelectric	Resource Power Conversion	Dams and Reservoirs	Dam rupture	x			x		Plant damage due to survey oversights
			Loss of water	x			x		
			Overflow	x			x		
			Reservoir leaks		x		x		
			Boating accidents		x		x		Personnel in the course of duty
		Conversion (Turbines)	Flooding of the power house	x			x		
			Conduit failure		x		x		
			Turbine failure		x		x		
			Electrical fires		x		x		
			Power interruption		x		x		
			Accidents involving equipment	x			x		
Geothermal	Exploration	Surveys	Airplane crashes		x		x		
			Auto accidents		x		x		
			Personnel injuries and illnesses		x	x			As a result of exposure to the elements and operations in remote areas.

(continued)

TABLE 1 (continued)

RESOURCE	ENERGY CYCLE ELEMENT	TECHNOLOGY AREA	ACCIDENT	SEVERITY Major	SEVERITY Minor	FREQUENCY OF OCCURRENCE Frequent	FREQUENCY OF OCCURRENCE Infrequent	FREQUENCY OF OCCURRENCE Hypothetical	REMARKS
Geothermal (continued)	Exploration (continued)	Drilling	Blowouts	x		x			Results in emissions of hot fluids/gases to environment or to aquifer, etc.
			Subsidence	x			x		
			Rig accidents		x		x		Including personnel operating rig
	Extraction	Drilling and Well operation	Blowouts	x		x			Same as exploration
			Induced seimicity & seismic induced failures	x			x		Wells and pipelines
			Leaks and ruptures	x			x		
			Landslides and erosion		x		x		Caused by poor drilling and construction practices
			Well failures		x		x		
			Subsidence	x			x		Probably not in vapor-dominated fields
			Rig failure	x			x		Usually as a result of a blowout or seismic activity
			Explosion	x			x		Gas ignition (organic fluids)

(continued)

TABLE 1 (continued)

RESOURCE	ENERGY CYCLE ELEMENT	TECHNOLOGY AREA	ACCIDENT	SEVERITY Major/	Minor	FREQUENCY OF OCCURRENCE Frequent	Infrequent	Hypothetical	REMARKS
Geothermal (continued)	Extraction (continued)	Pipeline gathering system	Pipeline ruptures	x			x		A result of an earthquake or pressure buildup
			Pipeline leaks		x		x		
	Conversion		Burns		x		x		
			Mechanical accidents		x		x		
			Fire		x		x		Isobutane mixtures in the isobutane cycle.
Oil Shale	Exploration	Mapping and drilling	Automotive equipment accidents, unforeseeable exposure to elements of nature		x		x		Common to any activity associated with resource evaluation in remote areas.
	Resource Extraction	Surface mining Blasting to rubbleize structure	Explosion before personnel and equipment clear the area		x		x		
		Forming the pit	Landslides entrapping personnel and/or equipment		x			x	
		Excavating the mineral	Slips, falls and equipment related accidents		x	x			

(continued)

TABLE 1 (continued)

RESOURCE	ENERGY CYCLE ELEMENT	TECHNOLOGY AREA	ACCIDENT	SEVERITY Major	SEVERITY Minor	FREQUENCY OF OCCURRENCE Frequent	FREQUENCY OF OCCURRENCE Infrequent	FREQUENCY OF OCCURRENCE Hypothetical	REMARKS
Oil Shale (continued)	Resource Extraction (continued)	Underground mining Forming rooms and pillars	Roof collapse	x			x		Proper roof bolting can avoid this
			Blasting accidents	x			x		
			Dust explosions	x			x		
		Mine ventilation	Failure of equipment		x		x		
		Removal of mineral	Automotive equipment accidents		x	x			
			Vehicle/vehicle-pillar collisions		x		x		
			Falls from tall equipment		x		x		
			Landslides affecting haulage road		x		x		
			Land subsidence	x				x	
	Shale Preparation	Crushing, conveying, and screening	Accidents involving machine operation		x	x			

(continued)

TABLE 1 (continued)

RESOURCE	ENERGY CYCLE ELEMENT	TECHNOLOGY AREA	ACCIDENT	SEVERITY		FREQUENCY OF OCCURRENCE			REMARKS
				Major	Minor	Frequent	Infrequent	Hypothetical	
Oil Shale	Processing	Retorting (Oil shale)							
		Oil-Shale charging	Conveyor belt accidents		x		x		
		Fuel supply system	Explosions	x			x		
		Shale-Oil recovery	Oil spills		x		x		
		Spent-Shale discharge	Conveyor belt accidents		x		x		
			Fires and burns generated by hot spots in spent shale		x		x		
		Refining (Shale Oil)							
		Storage (Tank farms)	Oil spills and fires		x		x		
		Hydrogenation	Explosions and equipment rupture	x			x		High-pressure operation
		Coking	Conveyor belt accidents		x		x		

(continued)

TABLE 1 (continued)

RESOURCE	ENERGY CYCLE ELEMENT	TECHNOLOGY AREA	ACCIDENT	SEVERITY Major	SEVERITY Minor	FREQUENCY OF OCCURRENCE Frequent	FREQUENCY OF OCCURRENCE Infrequent	FREQUENCY OF OCCURRENCE Hypothetical	REMARKS
Oil Shale (continued)	In-Situ Recovery	Drilling Blasting Igniting Retorting Gas Recycling Oil Recovery	Surface accidents involving blasting and machinery		x	x			Underground site probably will be too deep for surface effects. No personnel present underground during retorting operation
		Preparation of Underground Site	Same as for underground mining		x		x		
	Product Transportation	Pipeline Rupture	Oil spills under or above ground	x			x		
			Localized fires		x		x		
		Pump Failures	Oil spills in pump house		x		x		
	Land/Reclamation/Oil-Shale Disposal	Groundwater Control	Failure of retaining dams or embankments	x			x		Mineralized water can contaminate public water supplies
		Materials Handling	Surface accidents involving machinery		x	x			
Solar Energy	Direct Conversion Photovoltaic	Electrical Energy Production	Solar cell breakage		x		x		
			Wire damage or breakage		x		x		
			Solar cell failure		x		x		
			DC/AC converter failure		x		x		
			Electrical fire		x		x		
			Injuries (burns, falls)		x	x			

(continued)

TABLE 1 (continued)

RESOURCE	ENERGY CYCLE ELEMENT	TECHNOLOGY AREA	ACCIDENT	SEVERITY Major/Minor		FREQUENCY OF OCCURRENCE Frequent			REMARKS
				Major	Minor	Frequent	Infrequent	Hypothetical	
Solar Energy	Solar-Thermal	Solar to heat-energy conversion	Reflector damage	x			x		
			Water pipe rupture		x		x		
			Hot water storage failure		x		x		
			Mirror breakage		x		x		
			Heliostat failure		x			x	
			Boiler rupture/leak	x			x		Proposed liquid metal (Na or NaK) system
			Heat exchange fluid spill or leak		x			x	
			Injuries (burns, falls)		x	x			
		Electrical Energy Prod.	Steam turbine accidents		x		x		Same as for Geothermal, or Fossil Fuel-fired steam electric generating plant.
			Electrical fires		x		x		
		Miscellaneous	Structural failure	x				x	
	Solar-sea	Resource recovery	Pump failure		x		x		
			Corrosion (pipeline & other equipment)	x			x		
			Working fluid leak (other than water)		x			x	
			Boiler failure		x		x		
			Condenser failure		x		x		
			Turbine failure		x		x		
			Fire and explosion (energy storage)	x				x	

(continued)

TABLE 1 (continued)

RESOURCE	ENERGY CYCLE ELEMENT	TECHNOLOGY AREA	ACCIDENT	SEVERITY		FREQUENCY OF OCCURRENCE			REMARKS
				Major	Minor	Frequent	Infrequent	Hypothetical	
	Solar-Sea (continued)	Energy Transportation	Fire and explosion	x			x		
			Ship collision		x	x			
			Pipeline rupture		x		x		
		Miscellaneous	Storm damage		x			x	
	Wind Power	Resource recovery	Propeller blade breakage		x		x		
			Hub damage		x		x		
			Construction & erection accidents		x	x			
			Injuries during maintenance		x	x			For other than commercial units.
			Tower service elevator failure		x	x			
		Electrical Energy Prod.	Generator failure		x		x		
			Electrical fires		x		x		
		Miscellaneous	Structural failure (support tower)	x				x	
			Propeller striking surrounding objects		x			x	
	Tidal and Wave		Barrage failure or breaching	x			x		
			Gate failure		x		x		
			Pump & other machinery failure		x		x		
			Storm damage		x		x		
			Earthquake damage	x				x	
			Turbine failure		x		x		Same as for the Hydroelectric hydraulic turbine

(continued)

TABLE 1 (continued)

RESOURCE	ENERGY CYCLE ELEMENT	TECHNOLOGY AREA	ACCIDENT	SEVERITY Major	SEVERITY Minor	FREQUENCY OF OCCURRENCE Frequent	FREQUENCY OF OCCURRENCE Infrequent	FREQUENCY OF OCCURRENCE Hypothetical	REMARKS
	Tidal and Wave (continued)		Generator accidents		x		x		Same as for the hydroelectric generators
			Flooding		x		x		
			Navigation accidents		x		x		
	Biomass Conversion		Gas explosion	x			x		Same as for any combustion process.
			Fires		x		x		

TABLE 1 (continued)

RESOURCE	ENERGY CYCLE ELEMENT	TECHNOLOGY AREA	ACCIDENT	SEVERITY Major	SEVERITY Minor	FREQUENCY OF OCCURRENCE Frequent	FREQUENCY OF OCCURRENCE Infrequent	FREQUENCY OF OCCURRENCE Hypothetical	REMARKS
All	End Use	Generation of Electricity							
		Boiler Fired Plant	Explosion	x			x		
			Implosion		x		x		
			Tube rupture		x		x		
			Scalding		x		x		
		Gas Turbine Plant	Explosion (mechanical or pressure)	x			x		
			Asphyxiation		x		x		
			Rupture		x	x			
		Fuel Cell	Gas leak		x			x	
			Fire		x			x	
		MHD	Magnetic explosion	x				x	
			Burn-through press explosion		x			x	
			Asphyxiation		x			x	
			Failure of vent or vapor handling system	x				x	
			Leak in alkali metal vapor system		x			x	
			Alkali metal/water reaction	x				x	
		General	Fire and explosion	x			x		
			Power failure		x	x			
			Flooding		x		x		
			Electrical fires		x	x			
			Occupation injuries		x	x			
			Fuel leaks (liquid and vapor)		x	x			
			Oil leaks (containing PCB)		x		x		May affect residents of area

(continued)

TABLE 1 (continued)

RESOURCE	ENERGY CYCLE ELEMENT	TECHNOLOGY AREA	ACCIDENT	SEVERITY Major	SEVERITY Minor	FREQUENCY OF OCCURRENCE Frequent	FREQUENCY OF OCCURRENCE Infrequent	FREQUENCY OF OCCURRENCE Hypothetical	REMARKS
All	End Use	Transmission and Distribution of Electricity	Ground fault		x	x			Causing possible fire or power failure
			Insulation failure		x		x		Causing possible fire or power failure
			Lightening strikes		x	x			
			Aircraft explosion	x			x		
			Ship collision (incl. tanker)	x			x		
			Farm equipment accidents		x	x			
			Aircraft collision (commercial)	x			x		
		Industrial	Plant fire/explosion	x			x		
			Plant equipment failure		x	x			
			Plant flooding	x			x		
			Occupational injuries		x	x			
			Toxic substance effluent or emission	x			x		
			Pipe ruptures (water, gas, steam)		x	x			
		Commercial	Electrical fires		x	x			
			Occupational injuries		x	x			
			Building collapse	x			x		
			Pipe ruptures		x	x			
		Residential	Fires		x	x			
			Gas explosions		x	x			
			Falls in the home		x	x			
			Gas leaks		x	x			
			Storm damage		x	x			

(continued)

TABLE 1 (continued)

RESOURCE	ENERGY CYCLE ELEMENT	TECHNOLOGY AREA	ACCIDENT	SEVERITY Major	SEVERITY Minor	FREQUENCY OF OCCURRENCE Frequent	FREQUENCY OF OCCURRENCE Infrequent	FREQUENCY OF OCCURRENCE Hypothetical	REMARKS
		Residential (continued)	Appliance accidents		x	x			
			Heating and air conditioning equipment accidents		x	x			
			Flooding (storm or pipe break)		x	x			
			Home accidents		x	x			
			Electrocution		x	x			
			Asphyxiation		x	x			
			Trees falling on lines		x	x			
			Accidents knocking over power lines		x	x			
			Line breaks due to ice		x	x			
			Power failure due to wildlife short circuiting		x	x			
			Line overload		x		x		
			Storm damage		x	x			
			Corona discharge effects		x	x			Accidents affect human health, personal property, and the environment
			Occupational injuries		x	x			
			Electrical equipment failure		x	x			
			Fire		x	x			
	All		Electrocution		x	x			
			Hurricane	x			x		Major threat to energy facilities; 38% of oil processing and 74% of natural gas production is in vulnerable region.

(continued)

TABLE 1 (continued)

RESOURCE	ENERGY CYCLE ELEMENT	TECHNOLOGY AREA	ACCIDENT	SEVERITY		FREQUENCY OF OCCURRENCE			REMARKS
				Major	Minor	Frequent	Infrequent	Hypothetical	
			Tornadoes	x		x			18% of crude processing capacity and 12% of natural gas production in high risk region.
			Floods	x		x			Minor threat to national total oil, gas and coal production.
			Tsunamis	x			x		
			Snow and Ice Storms		x	x			
			Earthquakes	x		x			18% of crude refining capacity, 3% of gas production and 15% of coal production located in areas of major seismic risk.
			Land Subsidence	x			x		
			Avalanches and Landslides	x			x		
			Volcanoes	x			x		Insignificant threat to United States energy facilities.
			Meteorites		x		x		

(continued)

TABLE 1 (continued)

RESOURCE	ENERGY CYCLE ELEMENT	TECHNOLOGY AREA	ACCIDENT	SEVERITY	FREQUENCY OF OCCURRENCE			REMARKS
				Major/Minor	Frequent	Infrequent	Hypothetical	
			Airplane and Missile Crashes	x		x		Crashes of airplanes occur frequently for general aviation but infrequently for commercial aviation.
			Sabotage	x	x			
			War	x		x		

[a]Frequency refers to the number of times an event occurs in the United States rather than the number of times the event effects energy related facilities.

available. In these instances, accidents, frequencies, and severities were based on subjective assessment of the technologies involved.

The emphasis of each chapter of the report is on major accidents or minor accidents which cumulatively have a major effect. Because of the limited time available for completion of the report (ca. 6 weeks), the report was restricted to summarizing available data. Detailed risk analyses were not performed. No attempt was made to collect a new and consistent set of data which would allow comparison of one energy resource area to another. Thus, only limited comparisons are made of accident risks among resource areas.

A separate chapter or part of a chapter is devoted to each resource area. Because most end uses are common to more than one energy system, a separate chapter is devoted to this subject. Similarly, unscheduled events such as hurricanes affect more than one energy system and are treated in a separate chapter.

SECTION 2.0

SUMMARY

Accidents can occur at all steps in the energy cycle for all enery systems, nuclear and non-nuclear. They can be caused by human error, structural or mechanical failure, sabotage and natural phenomena such as hurricanes and earthquakes. These accidents can cause environmental damage, economic losses, fatalities, injuries, and health impairment. A summary of the frequency and severity of representative accidents for the coal, crude oil, natural gas, LNG, hydroelectric, geothermal, oil shale and solar energy systems appears in Table 1.

Although data are available from many sources, it is difficult to assess the relative risk of accident occurrence among the principal non-nuclear energy systems because of the lack of consistent data recording and reporting. However, based on the best available estimate, there probably are a significantly greater number of deaths and injuries associated with the coal resource system per megawatt delivered than with the crude oil or natural gas systems (Table 2).

TABLE 2

ANNUAL DEATHS AND INJURIES ASSOCIATED WITH COAL, CRUDE OIL, AND NATURAL GAS FIRED ELECTRICITY SYSTEMS FOR A 1000 MEGAWATT POWER PLANT WITH A LOAD FACTOR OF 0.75[a]

	COAL		CRUDE OIL			NATURAL GAS
	DEEP	SURFACE	ONSHORE	OFFSHORE	IMPORT	TOTAL
Fatalities	4.00	2.64	0.35	0.35	0.06	0.20
Injuries	112.3	41.2	32.3	32.3	5.7	18.3

[a] Reference 1

Accidents associated with coal-related activities can be generic hazards (arising from participation in a particular activity in which the accident rate is generally independent of the coal fuel cycle, e.g., heavy equipment operation) or specifically coal-related hazards (a generic activity where accident rates for the coal fuel cycle are different from the industry-wide average, e.g., underground coal mining).

Underground coal mining is a significantly more hazardous occupation than underground mining of other substances and both are more hazardous than an all-industry average. The frequency of injuries in underground coal mines is more than three times the average for selected industries and about one and a half times the average for underground mining of other materials (Table 11). The severity of underground coal mining injuries was almost eight times the all-industry average and about 25% higher than underground mining per se (excluding coal).

Mine roof and rib falls have accounted for 40 to 50% of annual coal mine fatalities and haulage related accidents for about 15 to 20%. Gas or dust explosions can cause many deaths during a single incident but account for about 10% or less of the annual underground coal mining fatalities. Surface activities associated with underground coal mining and surface coal mining have accounted for approximately 20% of annual coal mining fatalities during the past 10 years. Significant health or environmental impacts also may result from mine tailing dam collapse or from land subsidence associated with coal extraction.[3]

Coal processing facilities (e.g., cleaning, sizing, drying operations) are less hazardous than other elements in the coal fuel cycle. The accident potential of coal conversion technologies which are being developed is not known. However, since most liquefaction and gasification processes operate at high temperature and pressure, accidents involving pressure vessel rupture may be expected. These accidents may release heavy metals and carcinogens.[3]

Other hazards associated with the coal fuel cycle are generic in nature. Accidents occur during transportation and distribution of coal via rail, truck, or ship.

Minor occupational accidents in the crude oil system are the most frequent and cumulatively are the most costly in terms of numbers of injuries, work days lost, and damage to equipment. Major accidents involve spillage, fire, and explosion. These accidents occur at each stage in the energy cycle. Oil spills occur on both land and water with the latter predominating in volume, frequency, and severity. Sources of spills include well blowout, tanker barge accidents, pipeline ruptures and leaks, other transportation accidents, and storage tank accidents. The greatest source of spilled oil is the tanker. Most spills are small, although a few major incidents account for much of the oil spilled. Coast Guard data for 1972 indicated that 19 spills accounted for 16.25×10^6 gallons whereas 10,126 spills accounted for 4.25×10^6 gallons.[4]

The major effect of an oil spill is damage to the environment including flora, fauna, and land. Studies indicate that the toxicity of the oil spill on marine species will vary in intensity depending upon the hydrocarbon fractions present and the type and age of the organisms affected. Effects of spilled oil range from minor disruptions of ecosystems with relatively rapid recovery to major disruptions with slow recovery. Marine birds which encounter oil spills generally perish from loss of insulation, and ingestion of oil from contaminated food, and preening. The severity of a spill depends on factors such as the volume spilled, the composition of the oil, wind, wave and current conditions, timeliness and effectiveness of cleanup procedures, and location of the spill.

Fire and explosion may result from spills of oil and refined products, both on and offshore. Major losses of life and property from such an event occur in refineries and tank farms. The largest and most severe refinery accident is the loss of hydrocrackers. Equipment losses from hydrocracker accidents have averaged more than $1 million a year since 1970. Potential economic losses as a result of storage tank fires and explosions are increasing due to increased crude oil and petroleum product prices and use of larger storage tanks and tank farms. Destruction of a single 500,000 barrel tank (replacement cost ∿ $2 million) filled with $10 a barrel oil can cause a $7 million loss.[5]

In the natural gas system, blowouts during drilling of exploratory and production wells, release of sulfur compounds during processing, and failures of pipelines account for the largest number of accidents. Sudden uncontrolled release of natural gas may result in explosions and fires causing damage to equipment and loss of life or injury to persons in the vicinity. The general public is exposed to pipeline hazards because they traverse populated residential and commercial areas.

Pipeline distribution accounts for the largest number of injuries and man-days lost in the natural gas system at 0.0138 injuries/10^{12} BTU and 0.324 man-days lost/10^{12} BTU, respectively. Most pipeline failures can be attributed to corrosion and damage by outside forces. Onshore extraction accounted for the largest number of casualties at $8.1 \times 10^{-5}/10^{12}$ BTU.[6] Other possible sources of natural gas accidents are malfunction of explosive charges or radioactive sensors during preliminary stages of exploration, failure of aboveground storage tanks and underground storage cavities, and malfunction of peak shaving plants. Accidents occurring during exploration are infrequent and not severe. Failure of an aboveground storage tank entails the loss of large amounts of gas and the potential for an explosion and large fire.

LNG is a hazardous material because of its cryogenic properties and flammability. Contact with LNG will cause damage to human tissue. On vaporization and exposure to source of ignition it will burn causing injury and loss of a life to persons in the vicinity as well as extensive equipment damage. It may also form a vapor cloud shich may travel great distances before igniting, thus increasing the damage area. The worst accident to date involving LNG occurred at a storage facility in Cleveland in 1944. The incident resulted in 130 deaths and $10 million damage. The probability of an accident occurring due to the same cause is low because of development of materials resistant to brittle failure at cryogenic temperatures.

Those LNG accidents which are considered to have the greatest potential for damage are failure of a storage tank, an aircraft crash into a docked ship, and a collision at sea involving an LNG tanker in which the contents of one or two tanks are released. Minor accidents include release of refrigerants, solids blocking the pipeline during or after the liquefaction process, onboard malfunctions of tankers, leaks in transfer systems from tanker to shore, and onshore maintenance.

The safety of shipping and storing LNG is a matter of significant controversy. Risk analyses have been performed for tanker collisions and failure of storage tanks. Because no good statistical data base exists, several methods of risk analysis are used. One approach is to extrapolate data from shipping accident records. Another approach involves theoretical modelling using event trees and probability estimates. Analytical and simulation approaches model the performance of a system in terms of appropriate performance parameters such as ship velocities and structural characteristics. One study indicated that the predicted fatalities would be 0.4 per year for tankers calling at ports in the United States between 1980 and 1985.[7]

Risk analyses for three California terminal sites performed by the Federal Power Commission (FPC), Science Applications, Inc. (SAI), and the El Paso Alaska Company have been compared. All studies indicated that the risk of a severe accident is low.[8] The likelihood of an accident occurring was estimated to be in the range of one accident per 10,000 years to one accident per 100,000 years.

The estimates of risk were not identical. The variation in results may be attributed to different approaches and initial assumptions. Examples of this include whether rammings and groundings are as potentially harmful as collisions, the number of tanks which will rupture, the probability of a plume forming versus immediate ignition, assumptions concerning site and equipment characteristics, and differences in ship casualty frequency modelling and vapor cloud characteristics modelling.

Few data exist concerning accidents in the hydroelectric power system; however, occupational injuries at hydroelectric power plants probably are less frequent and less severe than at coal, oil, and nuclear fired plants. A survey for 1972 indicated that occupational injuries at hydroelectric power plants occurred at about one half the frequency and with one tenth the severity of the average for all electric generating plants. These results cannot be verified, however, because some of the original data are not available. Personnel accidents are the most frequently occurring incidents. These accidents occur during construction, maintenance, and normal operations.

The most severe hydroelectric accident which can occur is dam failure. In the recent Teton Dam catastrophe, 9 people were killed, 8 were missing, 13,000 cattle were destroyed, and more than $500 million damage was caused. Dam failures can also cause ecological damage and loss of food and water supplies. Among the possible causes of dam failure are improper siting, improper construction, erosion, forces exceeding design criteria, and sabotage.

Flooding of the area above the dam also can be serious. Flooding is caused by heavy rainfall or thawing snow and ice and can be promoted by improper construction practices.

Because there is only limited experience with geothermal resources, data are sparse. The most severe anticipated accident would be a well blowout releasing hot fluids and steam to the surface and adjacent geologic structures. A blowout could cause injuries and damage to equipment. If natural gas were present, a fire also could result. A less severe accident would be a pipeline leak or rupture caused by an earthquake, mechanical failure, human error, or pressure buildup due to silica precipitation.

Geothermal resource development can also cause subsidence resulting in damage to buildings and equipment. In lowland coastal areas (e.g., the Gulf Coast), subsidence may cause flooding and salt water intrusion.

There are few data concerning accidents associated with oil shale resources because the technology required to recover the fuel value of shale is in the development stage. However, as with other energy systems, it is expected that the least severe accidents generally will occur most frequently.

It is unlikely that mining of oil shale will be as hazardous as mining of coal. Roof collapse is less likely to occur for an equivalent sized room because of the hardness of the shale. However, larger rooms are likely to be used in oil shale mining. Explosions in the mine due to buildup of flammable gases probably will not occur; however, explosive mixtures of dust may form.

Explosions and fires may occur in the processing of shale. The incidence of severe accidents is likely to be similar to that observed for other processes involving use of hydrogen under high pressure.

In fossil fueled power plants, electricity currently is generated by boiler fired or gas turbine plants. Major accidents in these systems result from explosion in a boiler, turbine, or generator. Explosion and fire generally occur because of fuel mishandling or component failure. Power failure may result from explosions from electrical malfunctions, breakdowns, circuit overloads, or human error, and from accidents involving transmission and distribution of electricity.

There has not been a significant history of accidents in the various solar energy conversion systems due to a lack of large scale development. The meager past experience and the suppositions based upon proposed energy conversion systems indicate that most expected accidents would be minor in severity and generally infrequent. Economic losses would be substantial only in a severe accident involving a large-scale central power facility, such as the loss of a solar-thermal tower costing $15 million. Occupational injuries for central solar power facilities have been estimated by the Jet Propulsion Laboratory at between 0.5 and 1.6 man-days lost per MW_e year.

Transmission and distribution accidents generally involve downed power lines resulting from vehicle crashes, storms, falling trees, and other causes. Occupational injuries frequently occur during the generation and transmission of electricity. A National Safety Council study in 1972 showed that the frequency rate for the electric utility industry was less than the average for all reporting industries with 6.42 injuries per million manhours exposure. However, the severity rate was higher with 1003 total days charged for injuries per million manhours exposure compared to 655 per million manhours exposure for all reporting industries for the period 1970-1972.[11]

The accidents occuring in the transportation sector are those involving motor vehicles, trains, planes, buses, farm vehicles, and marine craft. The greatest number of fatalities result from motor vehicle accidents, followed by farm vehicles, recreational boating, and general aviation. Most rail accidents causing fatalities are attributable to servicing and other non-train operations.

The greatest number of injuries in the transportation sector result from motor vehicle accidents. There are approximately 100 times as many vehicular injuries as there are injuries from total railroad operations and 20 times as many as there are from farm vehicles.

Major accidents associated with industrial end use are explosion, fire, and flooding. Industrial, commercial, and residential accidents are generally minor though frequent. The most common accidents are those which occur in the home; however, most are not energy related. Those which are energy end use related involve appliances, heating and air conditioning, cooking, and the use of electrical equipment.

Both natural and man-caused unscheduled events can cause injuries, deaths, adverse effects on health, and destruction of equipment in all non-nuclear energy resource and technology areas. Natural incidents include hurricanes, tornadoes, floods, tsunamis, snow and ice storms, eqrthquakes, land subsidence, avalanches and landslides, volcanic eruptions, and meteorite impacts. The man-caused events include airplane and missile crashes, sabotage, terrorism, and war activities.

The probability of external unscheduled events occurring and the damage caused by them is highly site specific. Based on the frequency of the event and the total national energy capacity threatened, hurricanes pose the most serious potential threat of all the natural disasters because a large percentage of petroleum and natural gas is extracted and processed in hurricane-prone areas. Tornadoes and earthquakes may be termed as a lesser but significant threat to energy production systems. The consequences of a large meteorite impacting at or near a major energy facility could be severe. The probability of such impacts are low and highly site specific.

The destruction potential of war is great. Given a postulated "typical nuclear attack", however, considerable energy production capacity (50% - 70%) should survive. The greatest destruction will occur in the Northeast, along the California coast, and at large industrial centers.

The threat of sabotage is serious within the energy industry. Saboteurs can include enemy agents, dissident groups, dissatisfied employees, and the mentally unstable. Industrial sabotage may also be performed by workers wishing to prolong a job. Depending upon intent, the actual destructive effect of sabotage ranges from slight to severe. Data concerning the effect of past sabotage activities and predictions regarding their future frequency are not available.

In general, the components most vulnerable to natural disasters and sabotage are centralized control rooms, power lines, power switching centers, and nodes in the pipeline networks. Many of these vulnerable points are in remote, unguarded, or easily accessible areas. Thus a small but knowledgeable group of saboteurs could cause a major interruption in the flow of fuel or electricity to the ultimate consumer.

SECTION 3.0

COAL

The use of coal as a fuel source for energy production has historically occupied a major portion of the U.S. market. However, the increased use of alternate fuel sources (e.g., oil, natural gas, uranium), coupled with adverse environmental impacts related to coal extraction and utilization, has reduced the national dependence on coal as a fuel source. In 1948, coal provided 48% of the U.S. energy supply, while in 1971 it supplied only 18%.[12] The major consumers of United States coal are shown in Table 3.[13] The declining domestic reserves of alternate fuel sources, when combined with the uncertainties associated with foreign supplies, has renewed interest in coal as the major fuel source for the next few decades. It is estimated that the United States possesses the largest percentage of the world's known recoverable coal resources (Table 4).[14]

The increased use of coal as a fuel source will depend, in part, on resolution of various environmental impacts resulting from coal extraction, conversion, and end use. Included in this cost/risk/benefit analysis of various energy systems is analysis of accidents occuring in the coal resource cycle. The following sections discuss possible adverse health or environmental impacts resulting from accidents associated with this cycle.

3.1 RESOURCE SYSTEM OVERVIEW

Of the available domestic reserves of coal, approximately 90% is found in four geographical areas: Rocky Mountains, Northern Great Plains, Interior, and Eastern regions. Although the characteristics of the coal deposits vary, the coal resource system (excluding end use) can be divided into exploration, extraction, processing, transportation and distribution, and land reclamation energy cycle elements. Technology options within the extraction and processing elements are shown in Figure 1.

3.1.1 Exploration

Thorough mapping of each coal seam is essential for planning the efficient operation of a specific mine. Available mapping techniques include review of geophysical and geochemical data, drilling and core samples of strata, and seismic, gravimetric, or magnetic measurements. Despite the availability of an array of exploratory tools, drilling remains the primary method for locating and mapping coal deposits.[15] Exploration costs for surface mines

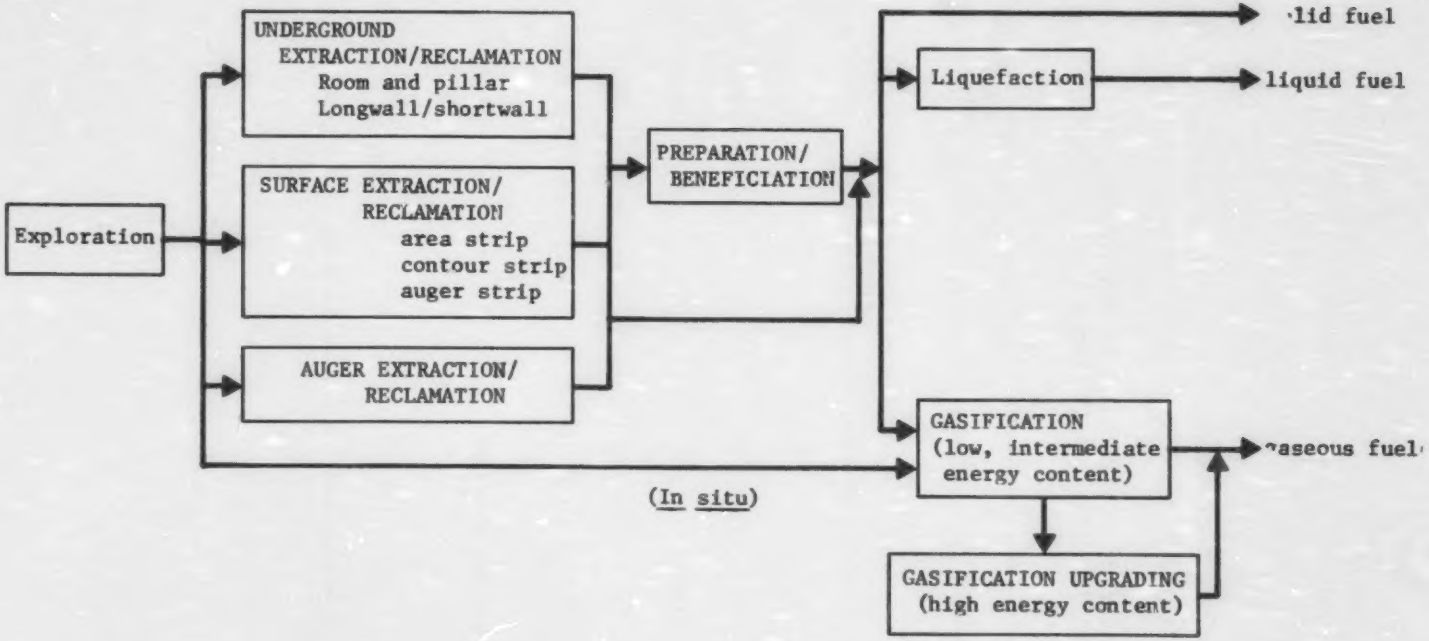
Exploration
UNDERGROUND EXTRACTION/RECLAMATION
Room and pillar
Longwall/shortwall
SURFACE EXTRACTION/ RECLAMATION
area strip
contour strip
auger strip
AUGER EXTRACTION/ RECLAMATION
PREPARATION/ BENEFICIATION
(In situ)
Liquefaction
GASIFICATION (low, intermediate energy content)
GASIFICATION UPGRADING (high energy content)
lid fuel
liquid fuel
aseous fuel

Figure 1. Coal resource systems technology options.

TABLE 3 CONSUMPTION OF BITUMINOUS AND LIGNITE COAL, BY CONSUMER CLASS, 1974[a]

CONSUMER	PERCENT OF TOTAL CONSUMPTION
Electric power utilities	70.6
Bunker, lake vessel, and exports	<0.01
Coke production	
Beehive ovens	0.2
By-product ovens	16.0
Steel and rolling mills	1.1
Other manufacturing and mining industries	10.5
Retail deliveries to other consumers	1.6
	100.0

[a] Reference 13.

TABLE 4. ESTIMATED COAL RESOURCES OF THE WORLD[a]

REGION	RECOVERABLE RESERVES[b] (%)	TOTAL RESOURCES[c] (%)
United States	30.8	27.2
Canada	0.9	1.0
Latin America	0.5	0.3
Europe	21.4	5.6
Africa	2.6	0.6
Oceania	4.2	1.9
U.S.S.R.	23.1	53.1
Peoples Republic of China	13.5	9.3
Asia, excl. USSR, China	3.0	1.0
	100.0	100.0
	(651×10^9 short tons)	(11.8×10^{12} short tons)

a. Reference 14.

b. That portion of total reserves currently exploitable under present local economic condition and available technology.

c. Total amount of coal in the earth's crust which can be successfully exploited in the foreseeable future.

consume approximately 10% of the total capital investment,[16] whereas exploration and mapping of underground mines account for less than 1% of the total capital invested.[17]

3.1.2 Extraction

Three coal extraction techniques are used today: underground, surface, and auger mining. Of the 604 million short tons of coal mined in 1974, 45.9% was mined by underground techniques, 45.5% by strip mining, less than 1% by auger techniques, and 7.9% by a combination of strip and auger methods.[13] The choice of mining method depends on a number of considerations, including seam depth and thickness, size of deposit, overburden characteristics, and local geology.

The majority of underground mines in the United States use either room-and-pillar techniques or longwall mining. The room-and-pillar method follows the coal seam, leaving intermittent pillars of coal to support the mine roof. Normal room-and-pillar mines remove about 45 to 50% of the actual coal seam.[15] The room-and-pillar technique can involve hand cutting and loading of coal, machine cutting and loading, or a combination of both. Mechanical cutting and loading is the preferred method; less than 0.2% of coal mined underground was hand loaded in 1974.[13]

In longwall mining, two access tunnels are dug parallel to the coal seam about 600 feet apart and a shearing machine is installed between them. The machine then removes the coal in the seam and transports it from the working face by conveyors installed in access passages. As the machine progresses along the seam, the roof collapses behind the working face. In longwall mining, roof collapse is anticipated, while in room-and-pillar mining, roof collapse is accidental and often fatal. An ancillary technique to the longwall technique is shortwall mining, where the working face is approximately 150 feet long, rather than 600 feet. Longwall mining normally recovers about 80% of the coal in the seam.[15]

Longwall mining in the United States is increasing slowly; 3.8% of coal mined underground in 1974 used the longwall method, compared to 3.1% similarly mined in 1973.[13] Longwall and room-and-pillar mining methods require similar surface preparation (i.e., surface support facilities, initial access tunnels, etc.).

In surface mining, coal seams are exposed by removing the overburden, and excavated using several types of heavy equipment (i.e., mobile tractors or dozers, shovels, draglines, or wheel excavators). Explosive fracturing of overburden and coal seam preceeds removal. When mining occurs on uneven terrain, the overburden is removed to create a flat bench, from which the coal is subsequently removed (contour mining). On level terrain, trenches are cut in the overburden to expose the coal seam, and as mining progresses, the spoils are deposited into the previously mined area (area mining). Auger mining techniques use large drills or augers to pull the coal out from a horizontal coal seam. Auger techniques may be applied to the exposed coal after overburden removal.

3.1.3 Transportation and Distribution

After removal from the coal seam, coal must be transported to a processing facility (if required) and eventually to the consumer. Underground mining operations generally use conveyors or rail shuttle cars to remove the coal from the working mine. In 1974, about 9% of underground mined coal was moved by conveyors, while 81% was removed by shuttle or rail cars.[13] The remaining coal was transported by truck or slurry pipeline. Surface mine haulage systems include large trucks or conveyor systems. The distribution of the coal to ultimate consumers usually is achieved by rail (unit or mixed train), truck, slurry pipeline, barge, or conveyor system. Table 5 indicates the most common methods of shipment of coal in the United States.[13]

3.1.4 Processing/Beneficiation

Prior to consumption, mined coal is usually subjected to some degree of cleaning or sizing. In certain instances, coal is converted into solid (coke), liquid, or gaseous products prior to combustion. Table 6 presents the amount of coal mined in 1974 which is subjected to cleaning or preparation steps prior to conversion or combustion.[13]

Approximately 15% of the total 1974 coal production was used to make coke for metallurgical smelting operations.[13] Coke is the residue remaining after destructive distillation of coal. Of the total coke production in 1974, approximately 1.5% was produced in beehive ovens (where the volatile constituents are not recovered) and the remainder in by-product coke ovens (where the volatile components are recovered).

Coal also can be converted into liquid or gaseous products in order to improve its quality prior to end-use. Gaseous fuels of low, intermediate, or high energy content can be produced from coal. Low and intermediate energy content gases are produced in a two-stage process involving preparation and gasification; a third stage, upgrading, is required for the production of high energy value gases.

In the production and upgrading of gaseous fuels from coal, the carbon-to-hydrogen ratio is changed - the smaller the ratio, the higher the energy content. Either hydrogen has to be added to the production gases or carbon removed. Numerous gasification processes are described in Table 7, along with process requirements and operating conditions.[13,18] Several methods are available for reducing the carbon-to-hydrogen ratio in the production of liquid fuels; hydrogenation, pyrolysis, and catalytic conversion. Coal liquefaction methods are described in Table 8, along with process operating parameters.[13,18] Most processes described in Table 7 and 8 are still in developmental stages, so many of the operating characteristics remain undefined.

3.1.5 Reclamation

Although the large areal disturbances of surface mining are generally more visible, both underground and surface mining operations require land reclamation. The disposal of mine tailings can be accomplished by reinjection into spent mine shafts for underground mine operation, or by placement

TABLE 5. BITUMINOUS COAL AND LIGNITE SHIPMENT METHODS, 1974[a]

METHOD	QUANTITY (THOUSANDS OF SHORT TONS)	PERCENT OF TOTAL
Railroad	397,161	65.8
Waterway	67,754	11.1
Truck	66,382	11.0
Mine-mouth consumption	66,635	11.1
Other[b]	5,474	1.0
	603,406	100.0

a. Reference 13.

b. Includes coal used at the mine for power and heat, coal used by mine employees, and coal shipped by slurry pipeline.

TABLE 6. BITUMINOUS AND LIGNITE COAL PREPARATION, 1974[a]

PREPARATION METHOD	PERCENT OF TOTAL PRODUCTION SUBJECT TO TREATMENT[b]	
Mechanical cleaning		43.9
Underground[c]	64.9	
Surface[d]	29.5	
Augers[e]	7.9	
Crushing and screening		48.7
No processing		7.4
		100.0[f]

a. Reference 13.

b. Total 1974 production: 603,406 thousand short tons.

c. Total 1974 underground production: 277,309 thousand short tons.

d. Total 1974 strip mine production: 275,041 thousand short tons.

e. Total 1974 auger mine production: 51,056 thousand short tons

f. Six percent of all coal mined also was thermally dried.

TABLE 7. SELECTED FEATURES OF GASIFICATION PROCESSES[a]

PROCESS	REACTOR TYPE	COAL REQUIREMENTS	BED TYPE	OPERATING PRESSURE
Low and intermediate BTU gasification				
Lurgi	Gasifier	Noncaking coal; sizing required (no fines)	Modified fixed	300-450 PSI
Koppers-Totzek	Gasifier	Caking or noncaking; pulverizing required	Entrained suspension	Atmospheric
Bureau of Mines	Gasifier	Caking or noncaking; pulverizing required	Modified fixed	Atmospheric to 300 PSI
Westinghouse	Gasifier	Caking or noncaking; pulverizing and drying required	Fluidized	200-300 PSI
Ash agglomerating	Gasifier	Caking or noncaking pulverizing required	Fluidized	Pressurized
Applied Technology Corp. (ATC)	Gasifier	Pulverizing required	Molten iron bath	
In Situ gasification	-	Channelized coal seam; surface support facilities	-	Unknown
High BTU gasification				
Lurgi	Gasifier	Noncaking coal; sizing required (no fines)	Modified fixed	300-500 PSI
HYGAS (Steam oxygen or electrothermal	Hydrogasifier	Sizing required (8 to 100 mesh); heating and slurry	Fluidized	1000 PSI
BY-GAS	Gasifier and hydrogasifier	Pulverized; liquid slurry (to rank A)	Entrained flow	1000 PSI
SYNTHANE	Gasifier, devolatizer	All coals, 200 mesh; sizing heating, and volatizing required	Fluidized	1000 PSI
CO_2 acceptor	Gasifier, devolatizer	Lignite or subbituminous; sizing required	Fluidized	150 PSI

a. References 13, 18.

TABLE 8. SELECTED FEATURES OF LIQUEFACTION PROCESSES[a]

PROCESS	REACTION TYPE	COAL REQUIREMENTS	REACTOR TEMPERATURE (°F)	OPERATING PRESSURE
Synthoil	Hydrogenation	Pulverized, dried; caking or noncaking	850	2,000-4,000 PSI
H-Coal	Hydrogenation	Pulverized, dried; caking or noncaking	850	2700 PSI
Solvent Refined Coal (SRC)	Solvation, Hydrogenation	Pulverized, dried; caking or noncaking	800	1000 PSI
Consol Synthetic Fuel (CSF)	Hydrogenation	Pulverized, dried; caking or noncaking	800	1000 PSI
COED (Coalcon)	Pyrolysis	Pulverized, dried; caking or noncaking	600-1600	6-10 PSI
TOSCOAL	Pyrolysis	Pulverized, dried; caking or noncaking	970	Atmospheric
Fischer-Tropsch	Catalytic conversion	Depends on process	-	330-360 PSI
Methanol	Catalytic conversion	Depends on process	unknown	unknown

a. References 13, 18.

in strip mine trenches for surface mines. The surface storage of these tailings in earthen dams prior to ultimate disposal is a common practice. Land reclamation may also be required where raw or processed coal awaiting shipment or consumption has been stored. In all instances, the movement or removal of coal or spoils piles is accomplished with large earth-moving equipment common in the construction trades. Planned or unplanned land subsidence may occur in some cases, especially when underground mining or in situ gasification is used. The actions required to ameliorate impacts of subsidence will depend on local conditions.

3.2 ACCIDENT OVERVIEW

Accidents causing death, injury, or environmental damage can occur at any step in the coal fuel cycle. In Table 1, representative accidents which may occur have been identified. Severity and frequency estimates which appear in Table 1 are based on the definitions presented in the introduction.

Quantitative estimates of injury and death rates appear in Tables 9 and 10.[8,18,19] From these tables, it is apparent that the majority of occupational death and injuries occur in the underground mining and transportation sectors. It is noteworthy that the death and injury rates associated with underground mining are significantly greater than those associated with surface mining, either from their inherent severity, their frequency of occurrence, or a combination of both. Potential accident situations are discussed in the sections following.

3.2.1 Exploration

The human health or safety hazards associated with accidents during coal exploration activities are few. All hazards identified are generic in nature, with no specific coal exploration activity having an unusual accident type or frequency. Although a significant amount of coal seam mapping must occur prior to actual mining operations using drilling and coring equipment or explosives, no significant accidental health, safety, or ecological hazards are present.

3.2.2 Extraction

Historical data indicate that coal mining is a dangerous occupation. Table 11 compares the risks associated with underground coal mining with other industrial activities.[2] Coal mining related injuries were both the most frequent and most severe. The threat to personal health or safety from mining accidents depends upon the extraction technique used, the location of the mine, the activity of the miner, the location of the individual inside the mine (underground miners), the experience of the mining crew, the equipment used, and safety precautions and procedures employed in the mine, and other factors.

Table 12 presents an historical perspective of mining fatalities by principal cause over the years.[3] The number and severity of injuries sustained at coal mines in 1970 are presented in Table 13 and frequencies of occurrences

TABLE 9. COMPARISON OF COAL RESOURCE TECHNOLOGY OPTIONS: HUMAN HEALTH AND SAFETY FROM ACCIDENTS[a]

FUEL CYCLE	TECHNOLOGY OPTION RESOURCE AREA	ACCIDENT RATE PER 10^{12} BTU EQUIVALENTS FATALITIES	INJURIES	MAN-DAYS LOST
Surface coal mining and reclamation	Northwest-area strip			
	Uncontrolled	0.0025	0.057	1.41
	Controlled[b,c]	0.0025	0.057	1.41
	Central-area strip			
	Uncontrolled	0.003	0.16	3.99
	Controlled[d]	0.003	0.16	3.99
	Northern Appalachian-area strip			
	Uncontrolled	0.005	0.12	2.49
	Controlled	0.005	0.12	2.49
	Northern Appalachian Contour			
	Uncontrolled	0.005	0.12	2.49
	Controlled[d]	0.005	0.12	2.49
	Central Appalachian Auger			
	Uncontrolled	0.0001	0.094	1.9
	Controlled[d]	0.0001	0.094	1.9
	Central Appalachian Contour			
	Uncontrolled	0.0018	0.164	3.30
	Controlled[d]	0.0018	0.164	3.30
	Southwest-area strip			
	Uncontrolled	0	0.059	0.678
	Controlled[c]	0	0.059	0.678
	Eastern coal-area strip			
	Uncontrolled	NC	NC	NC
	Controlled[d]	0.005	0.25	74
	Western coal-area strip			
	Controlled	0.0065	0.31	96
Underground coal mining and reclamation	Central			
	Room and Pillar			
	Uncontrolled	0.01	1.01	37.8
	Controlled	0.01	1.01	37.8
	Northern Appalachia			
	Room and Pillar			
	Uncontrolled	U	U	U
	Controlled	U	U	U

NC = not considered, U = unknown

a. Reference 18.

b. In controlled situation, land reclamation and water treatment considered part of mine operation; in uncontrolled situation, they are not considered

c. Five years assumed for land reclamation.

d. Three years assumed for land reclamation

(continued)

TABLE 9 (continued)

FUEL CYCLE	TECHNOLOGY OPTION RESOURCE AREA	ACCIDENT RATE PER 10^{12} BTU EQUIVALENTS FATALITIES	INJURIES	MAN-DAYS LOST
	Longwall			
	Uncontrolled	U	U	U
	Controlled	U	U	U
	Central Appalachia			
	Room and Pillar			
	Uncontrolled	0.022	0.955	3.42
	Controlled	0.022	0.955	3.42
Coal preparation/ beneficiation	Breaking and Sizing			
	Northwest			
	Uncontrolled	0	0.003	0.148
	Controlled	0	0.003	0.148
	Central			
	Uncontrolled	U	U	U
	Controlled	U	U	U
	Northern Appalachia			
	Uncontrolled	U	U	U
	Controlled	U	U	U
	Central Appalachia			
	Uncontrolled	U	U	U
	Controlled	U	U	U
	Southwest			
	Uncontrolled	0	0	0
	Controlled	0	0	0
	Cleaning including washing[b]			
	Uncontrolled	0.0026	0.0053	22.9
	Controlled	0.0026	0.0053	22.9
	Cleaning including washing[c]			
	Uncontrolled	NC	NC	NC
Coal gasification (low, intermediate energy content)	Central coal			
	BuMines			
	Atmospheric	U	U	U
	Pressurized	U	U	U
	Koppers-Totzek	U	U	U
	Northern Appalachian coal			
	BuMines			
	Atmospheric	U	U	U
	Pressurized	U	U	U
	Koppers-Totzek	U	U	U
	Northwest coal			
	BuMines			
	Atmospheric	U	U	U
	Pressurized	U	U	U
	Koppers-Totzek	U	U	U
	Lurgi	U	U	U

(continued)

TABLE 9 (continued)

FUEL CYCLE	TECHNOLOGY OPTION RESOURCE AREA	ACCIDENT RATE PER 10^{12} BTU EQUIVALENTS FATALITIES	INJURIES	MAN-DAYS LOST
	Eastern Coal			
	Agglomerating Fluidized Bed[b]	NC	NC	NC
Coal gasification (high energy content)	High-BTU gasification			
	Central Coal			
	HYGAS-steam-oxygen	U	U	U
	BIGAS	U	U	U
	Synthane	U	U	U
	Lurgi	U	U	U
	Northern Appalachian coal			
	HYGAS-steam-oxygen[b]	U	U	U
	BIGAS	U	U	U
	Synthane	U	U	U
	Northwest coal			
	HYGAS-steam-oxygen	U	U	U
	BIGAS	U	U	U
	Synthane	U	U	U
	Lurgi	U	U	U
	CO_2 acceptor	U	U	U
	Solid coal			
	Solvent refined coal			
	Northern Appalachian area	U	U	U
	Central	U	U	U
	Eastern coal			
	Chemical cleaning[b]	NC	NC	NC
	Liquefaction			
	Northwest area			
	CSF process	U	U	U
	SRC process	U	U	U
	Central area			
	CSF process	U	U	U
	SRC process	U	U	U
	SRC process[c]	NC	NC	NC
	Northern Appalachian area			
	CSF process	U	U	U
	SRC process	U	U	U
Transportation, in-mine	Northwest coal			
	Trucking			
	Uncontrolled	0	0.027	0.674
	Controlled	0	0.027	0.674
	Central coal			
	Trucking			
	Uncontrolled	U	U	U
	Controlled	U	U	U

(continued)

TABLE 9 (continued)

FUEL CYCLE	TECHNOLOGY OPTION RESOURCE AREA	ACCIDENT RATES PER 10^{12} BTU EQUIVALENTS FATALITIES	INJURIES	MAN-DAYS LOST
	Conveyor			
	Uncontrolled	U	U	U
	Controlled	U	U	U
	Mine rail			
	Uncontrolled	U	U	U
	Controlled	U	U	U
	Southwest coal			
	Trucking			
	Uncontrolled	0	0.015	0.171
	Controlled	0	0.014	0.171
Transportation, surface distribution	Unit train			
	Northwest coal	0.075	0.599	55.6
	Central coal	0.066	0.876	81.3
	Northern Appalachian coal	0.065	0.856	79.6
	Central Appalachian coal	0.062	0.767	71.4
	Southwest coal	0.067	0.0534	49.6
	Mixed or conventional train			
	Northwest coal	0.075	0.599	55.6
	Central coal	0.066	0.876	81.3
	Northern Appalachian coal	0.065	0.856	79.6
	Central Appalachian coal	0.062	0.767	71.4
	Slurry pipeline river barge			
	Central coal	0.0019	0.0032	0.243
	Northern Appalachian coal	0.0019	0.0032	0.243
	Central Appalachian coal	0.0019	0.0032	0.243
	Trucking			
	Northwest coal	0.032	0.692	45.4
	Central coal	0.032	0.692	45.4
	Northern Appalachian coal	0.032	0.692	45.4
	Central Appalachian coal	0.032	0.692	45.4
	Conveyor			
	Central coal	0	0	0
	Northern Appalachian coal	0	0	0
	Central Appalachian coal	0	0	0

TABLE 10. ANNUAL DEATHS, INJURIES, AND WORK DAYS LOST FOR UNCONTROLLED COAL-FIRED ELECTRICITY SYSTEMS ASSOCIATED WITH A 1,000-MEGAWATT POWERPLANT WITH A LOAD FACTOR OF 0.75[a]

OCCUPATIONAL HEALTH	EXTRACTION						TOTAL	
	DEEP[b]	SURFACE[b]	PROCESSING[b]	TRANSPORT[c,d]	CONVERSION[e]	TRANSMISSION	DEEP	SURFACE
Deaths	1.67	0.308	0.0238	2.30	0.012	NA	4.00	2.61
Injuries	85	13.9	2.56	23.4	1.38	NA	112.3	41.2
Workdays lost	4,678[f]	499	99.5	2,340	152.9	NA	15,280	3,091

NA = Not Available

[a] Reference 1.

[b] References 3, 19.

[c] Impacts of coal based on coal transport exclusively by rail (ave. distance 300 mi.); annual coal supply for a 1000 MWe plant is 0.1% of total national ton-mileage.

[d] Assumed that average injury leads to loss of 100 workdays.

[e] Assumed one-half the combined deaths and permanent injuries are assumed to be fatal injuries. Permanent total disabilities are considered to represent 6,000 workdays lost, and other disabilities are estimated at 100 days lost.

[f] Excluding workdays lost attributed to complicated pneumoconiosis.

TABLE 11. INJURY RATES IN SELECTED INDUSTRIES, 1973[a]

INDUSTRY	FREQUENCY RATE[b]	SEVERITY RATE[c]
Automobile	1.60	176 (110)[d]
Chemical	4.25	397 (93)
Machinery	5.81	331 (57)
Petroleum	6.73	690 (103)
Shipbuilding	7.08	653 (92)
Non-ferrous metals and products	9.31	712 (76)
Mining, surface[e]	9.75	1365 (140)
Tobacco	12.03	404 (34)
Construction	13.59	1544 (68)
Railroad equipment	14.23	1361 (96)
Quarry[e]	17.67	1825 (103)
Underground mining, except coal[e]	25.26	4431 (175)
Underground coal mining[e]	35.44	5154 (145)
All industries[f]	10.55	654 (62)

a. Reference 2; Reported by member companies of the National Safety Council. NSC members generally have better safety programs and lower injury rates than non-member companies. Data are not comparable to Bureau of Labor Statistics (BLS) rates for less severe injuries (requiring medical treatment but not involving days of disability).

b. Disabling injuries per 10^6 man-hours.

c. Lost time (hours) per 10^6 man-hours.

d. Average days charged per case.

e. Based on data for 1972.

f. Rates not fully comparable from year to year due to reporting inconsistencies.

TABLE 12. FATALITIES IN ALL COAL MINES, BY PRINCIPAL CAUSE, 1906-1970[a,b] (Percent of Total)

	UNDERGROUND WORKINGS										
FIVE-YEAR PERIOD	FALLS OF ROOF AND FACE	HAULINGS	GAS OR DUST EXPLOSIONS	EXPLOSIVES	ELECTRICITY	ALL OTHER UNDERGROUND	TOTAL UNDERGROUND	SHAFT AND SLOPE	TOTAL	SURFACE[c]	AVERAGE NUMBER FATALITIES PER YEAR
1906-1910	44.5	12.2	18.0	7.6	2.2	5.9	90.4	2.9	93.3	6.7	2,657
1911-1915	47.0	15.3	14.5	5.9	3.4	4.6	90.8	2.4	93.2	6.8	2,517
1916-1920	48.1	18.4	8.8	6.0	3.3	4.7	89.2	2.2	91.4	8.6	2,420
1921-1925	47.3	16.5	15.3	5.0	3.6	4.6	92.2	1.7	93.9	6.1	2,215
1925-1930	51.1	17.0	13.5	4.0	3.9	4.5	94.0	1.1	95.1	4.9	2,235
1931-1935	55.1	16.7	6.5	3.1	4.3	5.8	91.5	1.4	92.8	7.2	1,240
1936-1940	52.4	17.1	9.8	3.2	3.7	6.2	92.4	1.3	92.7	6.3	1,265

a. Reference 3.

b. Beginning with 1941, the cause classification in this historical series was changed as follows: (1) Fatalities in shafts and slopes have been included in "Underground workings" and are distributed according to the specified causes; prior to 1941 these deaths were grouped and shown as "Shaft and slope." (2) Fatalities from underground machinery accidents are grouped and shown separately; prior to 1941 such deaths were included in "All other underground." (3) Fatalities from roof or face falls caused by haulage equipment or machinery knocking out roof-support have been included in the respective haulage or machinery classifications; prior to 1941 such deaths were included in "Falls of roof and face." (4) Fatalities from pressure bumps and bursts and from inrush of water or material are included in "All other underground;" prior to 1941 such deaths were included in "Falls of roof and face."

c. Includes fatalities that occurred at all other work locations, including the associated surface works of underground mines, strip mines, culm banks, dredges, and mechanical-cleaning plants; beginning with 1955, includes fatalities in auger mines.

(continued)

TABLE 12 (continued).

FIVE-YEAR PERIOD	FALLS OF ROOF AND FACE	HAULAGE	GAS OR DUST EX-PLOSIONS	EXPLO-SIVES	ELEC-TRICITY	MACHINERY	ALL OTHER UNDER-GROUND	TOTAL	SURFACE	AVERAGE NUMBER FATALITIES PER YEAR
1941-1945	47.6	20.1	8.4	2.6	2.9	3.3	6.3	91.2	8.8	1,311
1946-1950	50.3	20.0	6.4	2.5	2.0	2.8	4.4	88.4	11.6	870
1951-1955	48.9	19.0	8.2	1.5	2.7	3.6	3.6	87.5	12.5	522
1956-1960	50.5	14.5	6.6	2.1	3.7	3.9	5.8	87.1	12.9	380
1961-1965	47.4	15.7	10.2	1.1	2.2	5.5	4.0	86.1	13.9	274
1966-1970	39.0	13.8	12.2	0.8	3.7	6.9	4.1	80.5	19.5	246

TABLE 13. NUMBER, AVERAGE, AND SEVERITY OF INJURIES AT COAL MINES IN THE UNITED STATES, BY PRINCIPAL CAUSES OF INJURY AND GENERAL WORK LOCATION, 1970[a]

PRINCIPAL CAUSES OF INJURY	INJURIES, ALL MINES FATAL	 NONFATAL	SEVERITY,[b] ALL MINES
Underground mines:			
Underground:			
Falls of roof	76	1,320	396
Falls of face or rib	6	363	150
Pressure bumps or bursts	1	12	523
Inrush of water	-	-	-
Other falling objects	-	164	35
Falls of persons	-	456	37
Handling materials	2	2,126	39
Handtools	-	413	40
Stepping on objects	-	173	26
Striking or bumping	-	61	26
Haulage	37	1,651	206
Explosions (gas or dust)	41	14	4,505
Explosives	3	70	382
Electricity	11	78	252
Machinery	26	1,471	159
Suffocation	-	4	6
Mine fires	1	22	273
All other	-	147	24
Pneumoconiosis	-	9	2,500
Total	204	8,754	191
Shaft and slope:			
Falls of roof	2	4	2,009
Falls of face or rib	-	2	59
Other falling objects	-	6	21
Falls of persons	-	24	48
Handling materials	-	41	28
Handtools	-	10	16
Stepping on objects	-	5	14
Striking or bumping	-	1	39
Haulage	-	44	37
Electricity	-	3	37
Machinery	-	10	43
All other	-	2	5
Total	2	152	111
Total, underground	206	8,906	190

a. Reference 3.

b. Severity: number of days charged multiplied by 10^6 divided by man-hours. All fatalities and permanent total disabilities have a standard time-loss charge of 6,000 days.

(continued)

TABLE 13 (continued)

PRINCIPAL CAUSES OF INJURY	INJURIES, FATAL	ALL MINES NONFATAL	SEVERITY,[b] ALL MINES
Surface:			
Falls or slides of coal or overburden	2	--	6,000
Other falling objects	--	14	20
Falls of persons	--	95	43
Handling materials	--	228	28
Handtools	--	50	66
Stepping on objects	--	13	6
Haulage	4	125	264
Explosives	--	1	7
Electricity	5	19	1,266
Machinery	3	30	731
Suffocation	--	1	32
Fires	--	1	14
All other	--	48	14
Total	14	625	180
Total, underground mines	220	9,531	189
Strip mines:			
Falls or slides of coal or overburden	7	33	1,069
Other falling objects	1	46	164
Falls of persons	--	276	26
Handling materials	2	360	68
Handtools	--	93	13
Stepping on objects	--	29	11
Striking or bumping	--	6	9
Haulage	4	207	159
Explosives	1	8	700
Electricity	2	21	539
Machinery	11	158	463
Fires	1	16	398
All other	--	93	15
Total	29	1,346	162
Other surface mining:[1]			
Falls or slides of coal or overburden	2	8	1,231
Other falling objects	--	2	41
Falls of persons	--	23	24
Handling materials	--	21	16
Handtools	--	11	3
Stepping on objects	--	2	18
Striking or bumping	--	1	6
Hauling	1	12	476

(continued)

TABLE 13 (continued)

PRINCIPAL CAUSES OF INJURY	INJURIES, FATAL	ALL MINES NONFATAL	SEVERITY,[b] ALL MINES
Machinery	1	27	307
Fires	--	2	49
All other	--	3	11
Total	4	112	244
Total, mining	253	10,989	186
Mechanical cleaning plants:			
Falling objects	--	15	210
Falling of persons	--	118	37
Handling materials	1	155	82
Handtools	--	35	16
Stepping on objects	--	5	22
Striking or bumping	--	5	26
Haulage	3	133	193
Explosions (gas or dust)	1	4	1,222
Electricity	--	9	10
Machinery	1	29	253
Fires	--	6	13
All other	--	49	12
Pneumoconiosis	1	--	6,000
Total	7	563	119
Grand total	260	11,552	183

during the period 1966 through 1970 are shown in Table 14. It is noteworthy that the average number of fatalities per five year period has declined significantly since early in the century. Governmental regulations, mine safety programs, union activities, and technological advances have all contributed to this decrease.

Roof, rib, and face falls accounted for about 50% of yearly mine fatalities until the mid 1960s and still are the most important cause of mine fatalities. Roof and rib falls also accounted for a substantial part of the nonfatal coal mining accidents. Although the number of persons hurt by a single roof or rib fall is small, the high frequency with which they occur leads to a high death and injury total. Causes of roof and rib failure are listed in Table 15.[3,20,21,19] Failure to comply with adopted conventional support systems or lack of a support plan was the leading cause of fatalities.

The second greatest hazard in underground mining involved mining equipment operation. An engineering safety analysis identified the need for standardization of controls for mining equipment, noting that the positioning and responsiveness of equipment controls varied with manufacturer.[22] Two causes of fatalities are often cited by members of the mining industry--lack of mining experience and age (youth being a surrogate for inexperience). In a recent study of these two variables as they related to underground coal mine fatalities, age was not found to be a significant factor, and mining experience, *per se*, was a weak factor compared to job task experience.[23]

Although explosions and fire are often the most newsworthy accidents associated with underground mining, only 10-12% of the annual mining fatalities were caused by these disasters from 1960 to 1970. In fact, the number of miners killed in mine explosions has been steadily declining. The apparent reversal in this trend from 1960 to 1970 (see Table 12) can be attributed to several large explosions in 1963, 1968, and 1970. Table 16 provides details of major underground mine disasters since 1961.[3]

As noted above, the frequency of injury and death at surface mines is significantly less than at underground mines. However, the number of accidents occurring at surface mines has been increasing because of increasing reliance on surface mining techniques. The relationship between surface mining activities and fatal and non-fatal injuries is shown in Table 17.[24]

3.2.3 Processing/Beneficiation

The processing of coal can be divided into four categories: preparation (cleaning, sizing, drying, etc.), coking, liquefaction, and gasification. Operational histories exist for the first two categories, while the last two generally are in various stages of development.

Mechanical coal cleaning facilities have been in operation for years. Table 13 provides some injury data for mechanical cleaning plants.[3] There are few fatalities at these plants. A majority of the non-fatal accidents are associated with haulage, materials handling, and falls. The potential for explosions involving dust or volatile components exists, but is not a significant

TABLE 14. STATISTICS ON INJURIES AND INJURY RATES AT COAL MINES IN THE UNITED STATES, 1966-1970[a,b]

ALL COAL MINES	YEAR 1966	1967	1968	1969	1970
Number of injuries:					
Fatal	233	222	311	203	260
Nonfatal	10,446	10,115	9,639	9,917	11,552
Total	10,679	10,337	9,950	10,120	11,812
Injury rates:					
Frequency per million man-hours:					
Fatal	0.96	0.92	1.33	0.85	1.00
Nonfatal	42.85	41.84	41.12	41.76	44.40
Frequency per million tons:					
Fatal	0.43	0.40	0.56	0.36	0.43
Nonfatal	19.15	18.04	17.42	17.42	18.94
Severity per million man-hours:					
Fatal	5,735	5,509	7,960	5,129	5,996
Nonfatal	1,973	2,190	2,553	2,230	2,312
Severity per million tons:					
Fatal	2,563	2,375	3,372	2,140	2,558
Nonfatal	882	944	1,081	931	986
Average severity, days lost per injury:					
Permanent partial disability	620	621	763	600	756
Temporary total disability	32	33	37	36	33
All injuries	176	180	248	173	183

[a] Reference 3.
[b] Data exclude office workers.

TABLE 15. PRIMARY DEFICIENCIES RELATED TO ROOF AND RIB FALL FATALITIES; UNDERGROUND COAL MINES, 1967-1970[a]

PRIMARY DEFICIENCY	FATALITIES PER YEAR 1967	1968	1969	1970
Failure to take down or secure loose roof or rib	5	12	10	4
Failure to examine roof or incorrect analysis of examination	11	16	18	18
Failure to comply with adopted conventional support system or lack of support plan	34	35	20	25
Failure to use temporary support	12	17	11	14
Failure to follow rules or instructions, to heed warnings, or to take ordinary precautions	1	2	6	6
Failure to abandon workings when known to be imminently dangerous	3	3	3	5
Failure to follow or failure of roof-bolting plans	6	-	6	3
Failure of mining system	10	8	2	7
Failure to replace dislodged or removed supports	-	-	-	2
Failure of conventional support system	12	5	-	-
Other	-	-	1	-
Total deaths	94	98	77	84

[a] Reference 3, 19, 20, 21.

TABLE 16. MAJOR DISASTERS AT COAL MINES IN THE UNITED STATES, 1961-70[a,b]

DATE		MINE	LOCATION OF MINE	CAUSE	NUMBER KILLED
1961:	Mar. 2	Viking	Terre Haute, Ind.	Explosion	22
1962:	Jan. 10	No. 2	Herrin, Ill.	Explosion	11
	Dec. 6	Robena No. 3	Carmichaels, Pa.	Explosion	37
1963:	Apr. 25	Compass No. 2	Dola, W. Va.	Explosion	22
	Dec. 16	No. 2	Helper, Utah	Explosion	9
1964:	No major disaster				
1965:	May 24	No. 2A	Robbins, Tenn.	Explosion	5
	Oct. 16	Mars. No. 2	Wilsonburg, W. Va.	Mine fire	7
	Dec. 28	Dutch Creek	Redstone, Colo.	Explosion	9
1966:	June 1	Dora No. 2	Dora, Pa.	Suffocation	5
	July 23	Siltex	Mt. Hope, W. Va.	Explosion	7
1967:	No major disaster				
1968:	Aug. 7	River Queen No. 1	Greenville, Ky.	Explosion	9
	Nov. 20	Consol. No. 9	Farmington, W. Va.	Explosion	78
1969:	No major disaster				
1970:	Dec. 30	Nos. 15 and 16	Hyden, Ky.	Explosion	38
1971:	No major disaster				
1972:	July 22	Blackville No. 1	Blackville, W. Va.	Mine fire	9
	Dec. 16	Itmann No. 3	Itmann, W. Va.	Explosion	5

[a] A single accident in which 5 men or more are killed.
[b] Reference 3.

(continued)

TABLE 16 (continued)

DATE		MINE	LOCATION OF MINE	CAUSE	NUMBER KILLED
1973:	No major disaster				
1974:	No major disaster				
1975:	No major disaster				
1976:	March 9	Scotia mine	Oven Fork, Ky.	Explosion	15
	March 11	Scotia mine	Oven Fork, Ky.	Explosion	8

TABLE 17. FATAL AND NONFATAL INJURIES SUSTAINED DURING SURFACE STRIP MINING ACTIVITIES, 1966-1972[a]

SURFACE MINING ACTIVITY	PERCENT OF TOTAL ACCIDENTS, 1966-72 FATAL (%)	NON-FATAL (%)
Fall of highwall	12.9	1.0
Haulage Truck Operations	12.3	5.8
Dozer operations	6.4	2.1
Front-end loader operations	11.7	1.8
Shovel and dragline operations	9.4	2.7
Slips and falls	6.4	32.3
Railroad car dropping operation	9.4	1.5
Conveyors in preparation plants	8.1	3.0
Electrical systems	12.3	2.1
Handling materials	3.5	23.5
Machinery maintenance	7.6	24.1
	100.0	99.9

[a] Reference 24.

problem. The potential for fires or explosions from tailings resulting from coal preparation and treatment will be discussed in the reclamation section.

The coking of coal has been carried out since the turn of the century. Although there have been incidents of coke ovens or batteries exploding, the frequency of occurrence has been low. An accidental shift in operating conditions may cause an increase in fugitive emissions, some of which are known or suspected carcinogens.

Advanced processes involving coal liquefaction or gasification generally are in the developmental stage and no operating data exist to quantify accident situations. Some hypothetical incidents can be envisioned, but severity of impact or frequency of occurrence cannot be specified. It is evident from Tables 7 and 8 that the majority of coal conversion processes involve reaction vessels operating at elevated temperatures and pressures.[13,18] The failure of any portion of the system may cause fires or explosions. The rapid, explosive release of coal conversion reactants or by-products may include polycyclic aromatic hydrocarbons, or combustible gases. Some process steps such as rapid depressurization or volatilization are inherently dangerous. The use of pulverized coal as feedstock may provide an abrasive situation conducive to component failure. Coal feedstock systems may present fire hazards. Although accident data for these processes are not available, accident histories in other industries, e.g., oil refining, may be similar.

One gasification process is different from the rest: in situ gasification. The technology for in situ gasification is currently under development, but some severe problems have been recognized. The inability to control combustion in the coal seam may lead to explosive conditions. Explosive fracturing of the seam, required for controlled combustion, is a significant potential hazard. Should improper fracturing of the coal seam occur, reaction gases may escape and uncontrolled combustion may occur. Gases fed from the surface under pressure to support combustion present a potential fire hazard. Induced seismicity may result from gasification activities. Land subsidence after gasification is almost certain to occur. Unfortunately, insufficient information is currently available to quantify these risks.

3.2.4 Transportation and Distribution

From Tables 12, 13, and 17, it is evident that coal haulage in coal mining operations currently accounts for between 10 and 15% of mining fatalities.[3,24] In underground mining operations, the hauling subfunction is the most dangerous; that subfunction accounted for about 72% of total haulage accidents, and for 61% of all haulage-related man-days lost (of which 56% were compensable injuries). Loading subfunction accidents are low in frequency (about 10% of haulage-related accidents) but severe (27% of total function man days were compensable).[25] A worker at the controls of a vehicle is in a more dangerous location than a worker performing supporting tasks. Workers at the controls were involved in 82% of the total haulage related accidents, and accounted for 69% of the total man-days lost.[25]

Rail systems transport approximately 66% of coal produced to the consumer, 22% in unit trains, and 44% via mixed trains. Coal shipments represented 27%

of total rail freight in 1969 and 1970.[18,26] Estimated rail accident rates involving some form of coal transport are 0.06 fatal injuries and 0.585 non-fatal accidents (with 59.5 man-days lost per occurrence) for every 10^{12} BTU equivalent tons shipped.[18] Comparable analyses indicate slurry pipeline accident rates of 0.0019 fatalities and 0.0032 non-fatal injuries (with 0.24 man-days lost per occurrence) for 10^{12} BTU transported. Trucking rates are estimated at 0.032 fatalities and 0.69 non-fatal injuries (with 45.4 man-days lost) for 10^{12} BTU energy shipped. These accident projections are based on national statistics for motor freight carriers where assumed coal shipment accident rates are represented as the ratio of total coal shipped to total freight carrier tonnage for the time span in question. This assumes that the transport of coal presents no additional accident potential than the generic rate for all motor carrier transports. This assumption may not hold in those regions (e.g., Appalachia) where steep, unimproved roads may exist.

3.2.5 Land Reclamation

Land reclamation procedures during or after coal mining operations vary with the type and location of individual mining operations. Surface mining techniques (area and contour) and underground mining each require solution of special reclamation problems. Auger-mining represents a small portion of total coal production, and refuse generated by auger mining can be handled using the techniques practiced with underground or surface (strip) mining activities.

Surface or underground mining and associated coal preparation and treatment generate large quantities of tailings or spoils. The movement of these piles with large earth moving equipment provides accident situations similar to those in other construction areas (e.g., surface or underground mine site preparation). Human health and safety would not be expected to be substantially different from other earth moving operations.

In underground mining operations, it has been estimated that about 2.46 tons of solid waste are produced per 10^{12} BTU equivalent tons extracted, with about 4.38 acres of land undermined (assuming an average seam height of 5.3 foot).[18] For underground auger mining, about 5.5 acres are undermined for each 10^{12} BTU extracted. Of the area undermined, approximately 25% will subside.[18] Since subsidence affects a surface area greater than the area undermined, the estimates of total land subsidence resulting from mine subsidence in an average 600 foot deep mine is 10.2 acres per 10^{12} BTU equivalent tons extracted.* If the average life of a sizeable underground mining operation (room-and-pillar) is about 25 years, the time average land impact from subsidence is 127 acre-years per 10^{12} BTU extracted.[18] The time averaged land impact from subsidence in an auger mine is 51.1 acre-year per 10^{12} BTU. For longwall mining, where the mine roof collapses as mining progresses, it is assumed that subsidence occurs over the entire area undermined. The time averaged land impact from subsidence is estimated to be 280 acre-years per

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*Assuming 25% subsidence rate of the undermined areas of 4.36 acres/10^{12} Btus in a 600 foot deep mine.[18]

10^{12} BTU, over a 25 year mine life. Although rates of surface subsidence from mining activities can be estimated, the severity of impact depends upon the geographic location of the mine and facilities and resources in the affected area. In populated areas (e.g., Scranton, Pa.), subsidence has proven to be a severe problem, but in western coal tracts, subsidence may have no long term economic impact. However, disruption of western aquifers may result from either mining or subsidence.

Refuse piles from coal mining or preparation activities have often been used as earthen dams. Since the 1972 Buffalo Creek, West Virginia disaster, where a refuse pile dam collapsed killing 125 people, more emphasis has been placed on coal refuse piles as potential hazards. A preliminary assessment by the Bureau of Mines has indicated that more than 100 coal refuse impoundments in the Eastern regions present potential hazards.[27]

Not only can the refuse piles impound water, but they also may catch fire. Numerous smoldering fires have been reported. These fires can emit dense fumes and are difficult to extinguish. The remains after a refuse pile fire, or "red dog," can present disposal problems.

SECTION 4.0

CRUDE OIL

4.1 RESOURCE SYSTEM OVERVIEW

Oil was discovered in the United States in the middle of the 19th century. Until 1948, the United States was an exporter. The United States had a total proven reserve at the end of 1973 of 35.3 x 10^9 barrels (bbl) of crude oil.[28,29] By the end of 1975, proven reserves dropped to 32.7 x 10^9 bbl with an indicated additional reserve from known reservoirs of 5 x 10^9 barrels. These figures include the Gulf of Mexico.[29] The 1974 estimate of petroleum liquid resources in the United States was put at between 2 to 4 x 10^{11} bbl by the United States Geological Survey (USGS), while oil company estimates were only 8.8 x 10^9 bbl.[30]

There are several energy cycle elements involved in the discovery and transformation of crude oil into a usable fuel. The elements in this energy cycle are shown in Figure 2.

4.1.1 Exploration

Exploration is undertaken to locate geologic formations which may be potential oil reservoirs. This is generally a three phase effort which includes regional surveys, detailed surveys, and exploratory drilling.

Regional surveys, often conducted by plane or boat using a magnetometer, are used to identify promising geologic conditions where oil may be located. Detailed surveys then examine promising areas using seismic techniques and core drilling. The seismic technique uses an energy source to generate sound waves, which are detected and recorded on magnetic tape for data processing into cross-sectional maps of the subsurface geologic formations. Energy sources used include explosives in onshore exploration, propane/oxygen detonations in offshore exploration, or high-powered frequency oscillators in either location.

Core drilling for oil is employed where the situation warrants, using a rotary drill connected to a number of lengths of pipe called a drill string. The cuttings are analyzed to characterize the formation being penetrated and determine the presence of oil. The drilling technique uses a "drilling mud," a waterbased slurry of chrome lignosulfate of varying density, to remove drill cuttings and to maintain hydrostatic pressure in the hole to prevent a blowout (unconstrained flow of oil or gas). The drilling mud is circulated through the drill bit and back out the space between the drill pipe and the bore hole.

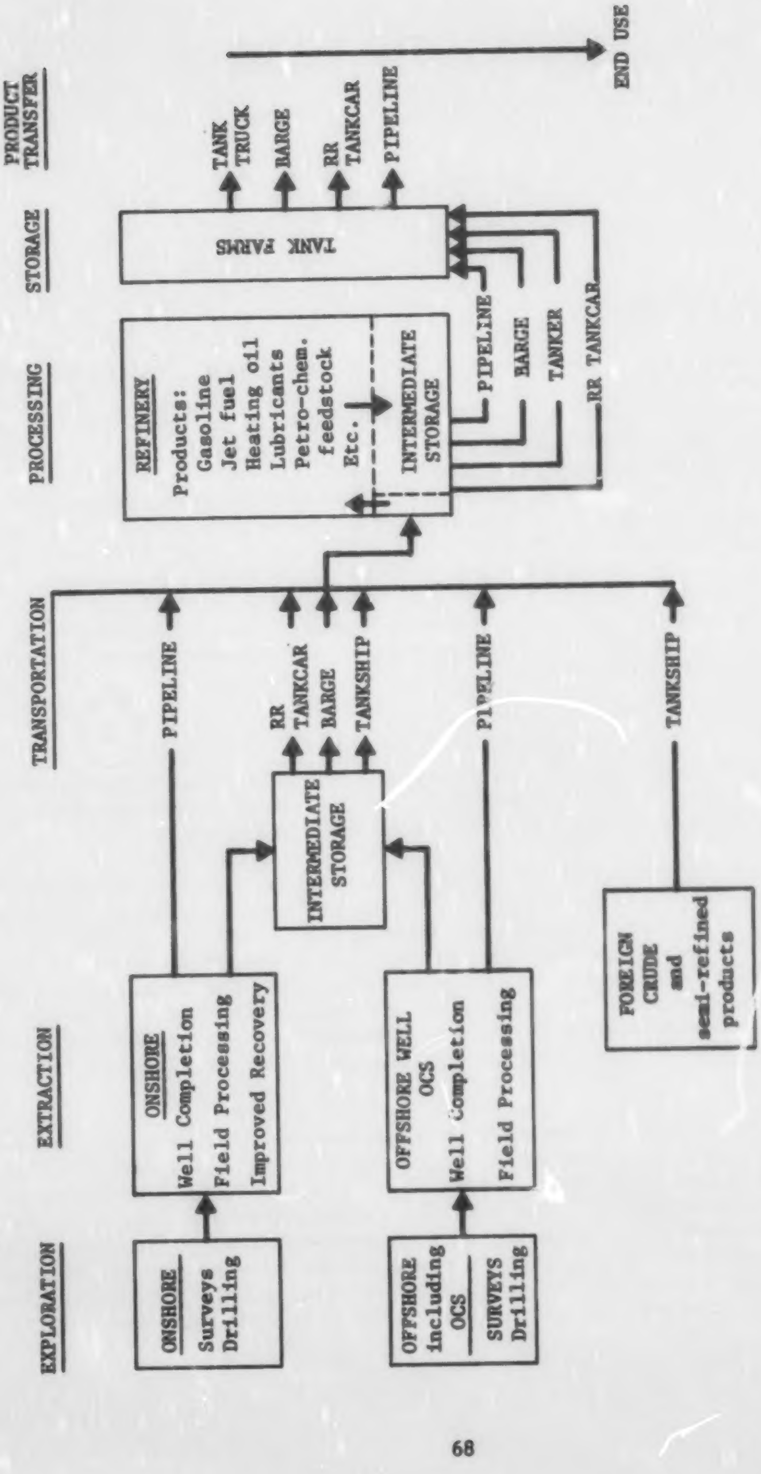
EXPLORATION
EXTRACTION
TRANSPORTATION
PROCESSING
STORAGE
PRODUCT TRANSFER
ONSHORE
Surveys
Drilling
OFFSHORE including OCS
SURVEYS
Drilling
ONSHORE
Well Completion
Field Processing
Improved Recovery
OFFSHORE WELL
OCS
Well Completion
Field Processing
FOREIGN CRUDE and semi-refined products
INTERMEDIATE STORAGE
PIPELINE
RR TANKCAR
BARGE
TANKSHIP
PIPELINE
TANKSHIP
REFINERY
Products:
Gasoline
Jet fuel
Heating oil
Lubricants
Petro-chem. feedstock
Etc.
INTERMEDIATE STORAGE
PIPELINE
BARGE
TANKER
RR TANKCAR
TANK FARMS
TANK TRUCK
BARGE
RR TANKCAR
PIPELINE
END USE

Figure 2. The crude oil cycle.

Offshore exploratory drilling requires a platform to support the drill rig and other equipment. The types of platform used are the permanently mounted jack-up, the moored barge, the dynamically positioned and moored drillship, and the dynamically positioned and moored semi-submersible.

Offshore exploratory drilling has been done mostly by mobile drilling units. A rig survey[31] for 1973 indicated 222 active rigs, 13 inactive, and 132 under construction. Of the active rigs, 127 were bottom supported. The number of floaters has been increasing, with 71% of those under construction being of this type. Presently 43% of the active rigs are floaters. It has been estimated that over the next 10 years the size of the mobile rig fleet will increase to between 250 and 400 units. It was estimated that approximately 520 mobile and platform mounted rigs would drill 200 wells during 1975.[31]

4.1.2 Extraction

When exploratory drilling indicates a discovery, the well is tested to determine the rate of oil flow and the size of the reservoir. If commercial production is warranted, a number of wells are drilled to drain the reservoir. Field processing equipment and pipelines are installed and positive controlled flow is maintained.

Development drilling uses the same techniques as exploratory drilling except that it is carried out with greater accuracy and precision. Offshore wells on the west and Gulf Coasts of the United States are drilled from fixed platforms. The wells are drilled into the reservoir, with cemented casings set and pipe installed to carry the oil to the surface. Offshore wells, and onshore wells in danger of wellhead damage (or in seismically active areas), have a downhole safety valve placed either near the bottom of the production pipe string or at least 100 feet below the sea floor. This valve is designed to close when the flow through it exceeds a certain limit. Wellhead valve controls, called Christmas Trees, are either pressure activated or operator controlled and control the flow rate from the well. Some offshore wells recently have been completed on the ocean floor rather than on a platform.

The oil removed from the well is processed to remove natural gas, production water (brine), sand, and other impurities. Natural gas can be separated using a gravity separator. The gas is transported by pipeline and sold, used as a lift in recovery of oil, or burned in a flare. Approximately 3.4% of all gas produced offshore is burned in a flare.[32]

Brine is normally separated by gravity. If it is emulsified in the oil other processing methods are required using heaters and surfactants. Additional treatment of brines using these methods and filters is required before disposal offshore. If possible, the sand produced is kept in the bottom of the well by means of chemical binders or screens. If some should surface, it is removed in the separators.

When the natural flow diminishes, additional oil can be retrieved using improved recovery techniques. One of these techniques is waterflooding or secondary recovery. This method involved pumping water down selected wells in a field to force up oil in other wells. All other improved recovery techniques are tertiary methods. The five categories of tertiary recovery techniques are polymer flooding, surfactants, miscible recovery processes, immiscible gases, and thermal recovery. Each involves adding a large quantity of a liquid or gas to the reservoir to improve the flow of oil.

4.1.3 Processing

A petroleum refinery converts crude oil into various products by means of a combination of processes. These processes include distillation, sulfur removal, cracking and reforming. Principal products of United States refineries are gasoline, jet fuels and kerosene, diesel and other fuels, lubricants, waxes and solvents, petrochemical feedstocks, and asphalt. The products and their proportions vary with refinery design, location, and time of the year. Feedstocks also can include natural gas liquids or synthetic crude from oil shale or coal liquefaction.

Crude oil is classified by density, sulfur content, and other impurities to meet the requirements of a particular refinery for efficient processing. Blending of various crudes is often necessary to achieve this.

The first step in refining oil is distillation. Distillation involves heating crude oil and separating components according to their boiling points. For example, gasoline boils at less than 250°F, while residual fuel oils boil at more than 900°F. The residual from distillation at atmospheric pressure is then distilled under vacuum to achieve further separation. The kinds of products produced will depend on the feedstock and the operating conditions of the distillation column.

Sulfur is removed by hydrodesulfurization. This process involves the reaction of hydrogen at high pressure (300-1000 psi) with the sulfur containing liquid at high temperatures (600-800°F) in the presence of a catalyst to form hydrogen sulfide (H_2S). A fractionation column is then used to separate the cleaned oil from the H_2S. The H_2S gas in the system ("sour gas") is circulated in a packed column with an amine solvent, which absorbs the H_2S. The solvent is regenerated, and the H_2S is processed to recover elemental sulfur.

Distillation alone may not produce products in the proper proportion to satisfy market demands. Thus further processing by cracking or reforming usually is necessary.

Cracking breaks large molecules in the feedstock into smaller molecules with a higher energy content. Catalytic cracking and hydrocracking are the two processes currently used in refineries. Catalytic cracking using catalysts of synthetic aluminum on solica in a fluidized bed design is the more widely used process. Hydrocracking involves reactions under high pressure (2000-2300 psi) and temperature (approximately 800°F) in the presence of hydrogen and a catalyst in a fixed-bed reactor design. There are fewer of these types of units because of high cost.

Reforming, alkylation, and isomerization processes rearrange the molecular structure of oil components to form high octane gasoline. All three methods use catalysts. Reforming uses platinum or rhenium in a hydrogen atmosphere at pressures of 100-200 psi and temperatures of 800-900°F. Alkylation uses acid catalysts, while isomerization uses platinum oxide at a temperature of 320°F and a pressure of 400 psi.

In addition to these process units, a refinery has a number of support facilities. These include stack gas cleaning equipment, wastewater treatment facilities, and facilities for generating hydrogen, steam, and electricity.

4.1.4 Transportation and Storage

Crude oil and petroleum products are transported by various means to refineries and markets. Among these are tank trucks, railroad tank cars, tankers, barges, and pipelines. The choice of mode of transportation depends on the distance to be traveled, the product to be transported, the availability of the transport system, and other factors. Data on the percentages of crude and refined products moved by the various modes of transportation is shown in Table 18.[33]

Tank trucks carry small quantities for distances less than 500 miles. Railroad tank cars are competitive with tank trucks for distances greater than several hundred miles and for tank car quantities. Tankers and barges are used for long-distance, large volume transportation via water routes, but are limited by available port facilities. Barges and tankers used for intracoastal shipping are generally limited to 125,000 ton tankers, being built for transporting Alaskan crude. Pipelines are competitive with waterborne and railroad transportation.

Pipelines are made of welded steel and are as large as 48 inches in diameter. Because of pressure drops along the line, pumping stations are installed every 50 to 150 miles. These stations use centrifugal pumps powered by electric motors or diesel engines. They are generally unmanned and remote controlled; however, periodic aerial inspections are made to detect leaks. Offshore pipelines are installed from pipelaying barges or ships and are placed in the bottom by air-blast trenching.

Crude and refined petroleum is stored in tanks ranging in capacity from several thousand barrels to 1 million barrels. Storage tanks often are grouped together in tank farms. Two types of storage tanks are used; the fixed cone roof and the internal floating roof. In the latter the roof moves with the internal level of liquid. Pipelines connect tank farms to loading facilities for transportation.

4.2 ACCIDENT OVERVIEW

Accidents in the crude oil resource system can occur at many points in the technology chain. These accidents involve equipment failure, human error, and natural phenomena. The consequences of these accidents include ecological

TABLE 18. PERCENTAGE OF CRUDE PETROLEUM AND PETROLEUM PRODUCTS MOVED BY METHOD OF TRANSPORTATION, 1938-1974.[a]

PERCENTAGE OF TOTAL TONNAGE SHIPPED

	PIPELINES		WATER CARRIERS		MOTOR CARRIERS		RAILROAD	
YEAR	CRUDE	PRODUCT[b]	CRUDE	PRODUCT	CRUDE	PRODUCT	CRUDE	PRODUCT
1938	71.01	6.35	25.58	52.65	1.17	10.59	2.24	30.41
1948	68.48	11.36	23.26	44.70	3.86	29.85	4.40	14.09
1958	76.35	20.48	16.90	37.51	6.45	36.76	0.30	5.25
1968	74.08	30.41	18.62	25.69	7.11	41.35	0.19	2.55
1970	74.30	31.12	18.90	26.75	6.65	39.72	0.15	2.41
1972	75.75	32.39	16.10	26.92	7.92	38.55	0.23	2.14
1973	76.89	32.74	14.13	25.78	8.68	39.31	0.30	2.17
1974	74.81	33.54	13.47	25.84	11.29	38.48	0.43	2.17

[a] Reference 33.

[b] Product pipelines move only light petroleum products.

damage, property damage, and injury or death. Representative accidents and their frequency and severity are shown in Table 1.

Although small spills account for most incidents, the cumulative amount of oil released is large. The most frequent accidents are those involving drilling rigs and trucks; however, refining accidents account for approximately one-third of the occupational injuries in the petroleum industry.[34] Occupational injuries and illnesses for 1975 for the exploration and production, drilling, refining, and pipeline and marine transportation of crude oil and products is shown in Table 19.[34]

A summary of fatalities for 1974 and 1975 for 137 oil and gas companies are shown in Table 20.[35] These data apply to on-duty accidents involving employees and do not cover those accidents affecting non-employees and private property.

Occupational health data are summarized on an energy equivalent basis in Table 21 and in terms of supplying a 1000 MW power plant with fuel for one year in Table 22.[1,15]

4.2.1 Oil Spills

4.2.1.1 Occurrence and Risk--

Although oil spills occur both on land and water, only those on water tend to be major in terms of environmental impact. This has prompted governmental regulations to prevent spills from occurring, and to contain them and clean them up when they do occur.

The Coast Guard, the Environmental Protection Agency (EPA), and the United States Geological Survey (USGS) share responsibility in this area. The Coast Guard has responsibility for all transportation related facilities and for all coastal, Ohio River, and Great Lakes spill incidents. EPA has responsibility for all onshore and offshore facilities not related to transportation. The U.S. Geological Survey is responsible for regulations for safe drilling and production practices of oil and gas activities on the outer continental shelf and inland spills.

Detailed reporting systems have been established by all three agencies to collect data of sufficient quantity, quality, and depth to permit trend and risk analyses. The Coast Guard established the Pollution Incident Reporting System (PIRS) in 1971 and the EPA began the Spill Prevention, Control and Countermeasure file (SPCC) in 1975. Information gathered by these systems can be retrieved in terms of source of spill, location of spill, causes, type of oil, and volume of discharge.

The USGS reporting system consists of two parts--inland and offshore. The inland monitoring system was started in 1974 and covers only those spills which occur on federal lands. Although there are field inspectors for inland spills, incidents are reported on the honor system.

TABLE 19. REPORT OF OCCUPATIONAL INJURIES AND ILLNESSES FOR THE YEAR 1975 COVERING OPERATIONS SUBJECT TO OSHA RECORDKEEPING REQUIREMENTS ONLY[a]

FUNCTION	NO. OF EMPLOYEES	RECORDABLE CASES INJURIES	RECORDABLE CASES ILLNESSES	TOTAL	FATALITIES	TOTAL LOST WORK DAY CASES	NON-FATAL CASES W/O LOST WORK DAYS
Exploration & Production[b]	54,598	2,466	36	2,502	9	763	1,730
Drilling[c]	1,918	515	0	515	2	196	317
Refining[d]	81,698	5,594	321	5,915	3	1,846	4,066
Pipeline-Crude & Production[e]	15,083	754	19	733	6	201	566
Marine[f]	3,108	173	0	173	2	66	105
Total	156,405	9,502	376	9,878	22	2,872	6,784

a. Reference 34.

b. Geophysical, seismographic, and geological operations, including incidental administrative work. Production operations, on- or off-shore, including maintenance and servicing of production properties and transportation of crews and materials.

c. Operation of on- and off-shore rigs including transportation, set-up, and dismantling.

d. Refining of crude oil to produce products including petroleum chemicals if the operation is an integral part of the refining operation.

e. Gathering systems and trunk line transportation of crude oil; pipeline transportation of refined and semirefined products.

f. Ocean, coast, and inland tankship and barge operations as well as land based marine department operations.

TABLE 19. (Continued)

	INCIDENCE RATES			
	TOTAL CASES	LOST WORK DAY CASES	NON-FATAL W/O LOST WORKDAYS	FREQ. RATE
Exploration & Production[b]	4.4	1.35	3.07	6.57
Drilling[c]	25.45	9.69	15.67	48.93
Refining[d]	7.20	2.25	4.95	5.57
Pipeline-Crude & Production[e]	5.01	1.30	3.67	6.52
Marine[f]	2.26	0.86	1.37	4.44
Total	6.04	1.76	4.15	6.49

TABLE 20 CAUSES OF FATALITIES IN THE PETROLEUM INDUSTRY, 1974 AND 1975[a]

FUNCTION	CASES REPORTED		FIRE AND EXPLOSION		STRUCK BY EQUIPMENT		MOTOR VEHICLE		AIRCRAFT		OTHER CAUSES	
	1975	1974	1975	1974	1975	1974	1975	1974	1975	1974	1975	1974
EXPLORATION AND PRODUCTION[b]	7	19	0	5	1	0	1	3	1	6	4	5
DRILLING[c]	2	1	0	0	1	1	0	0	0	0	1	0
REFINING[d]	2	10	1	3	0	4	0	1	0	0	1	2
PIPELINE-CRUDE & PRODUCTS[e]	4	5	2	0	0	1	2	0	0	0	0	4
MARINE[f]	2	1	0	0	0	0	0	0	0	0	2	1
TOTAL	17	36	3	8	2	6	3	4	1	6	8	12

a. Reference 35.

b.-f. See notes b.-f., Table 19.

TABLE 21. OCCUPATIONAL ACCIDENTS FOR CRUDE OIL AND PRODUCT TRANSPORT AND REFINING[a]

SYSTEM	ACCIDENT RATE PER 10^{12} BTU EQUIVALENTS FATALITIES	INJURIES	MAN-DAYS LOST
CRUDE OIL			
PIPELINE	6.9×10^{-5}	4.2×10^{-3}	1
PIPELINE	0.009	0.008	15
PIPELINE	NC	NC	NC
TANKER OR SUPERTANKER	U	U	U
OIL TANKER	0.0009	0.008	15
BARGES	U	U	U
OIL BARGE	0.0009	0.008	15
TANK TRUCK	U	U	U
TANK CARS	U	U	U
PRODUCT DISTRIBUTION PIPELINE	6.9×10^{-5}	4.2×10^{-3}	0.1
UNCONTROLLED TANKER OR SUPERTANKER	U	U	U
CONTROLLED TANKER OR SUPERTANKER	U	U	U
UNCONTROLLED SOUTH AMERICAN TANKER	U	U	U
CONTROLLED SOUTH AMERICAN TANKER	U	U	U
TANKER	NC	NC	NC
BARGES	U	U	U
TANK TRUCKS	U	U	U
TANK CARS	U	U	U

TABLE 21 (continued)

SYSTEM	FATALITIES	INJURIES	MAN-DAYS LOST
CANADIAN CRUDE/IMPORTED			
UNCONTROLLED	4.4×10^{-4}	0.0362	2.05
CONTROLLED	4.4×10^{-4}	0.0362	2.05
MIDDLE EAST CRUDE/ IMPORTED			
UNCONTROLLED	4.4×10^{-4}	0.0362	2.05
CONTROLLED	4.4×10^{-4}	0.0362	2.05
CONVENTIONAL REFINERY			
ARABIAN CRUDE	0.0014	0.11	25
KUWAIT CRUDE	0.0014	0.11	25
TOPPING REFINERY			
KUWAIT CRUDE	0.0014	0.11	25

a. Reference 15.

NC-not considered
U-Unknown

TABLE 22. ANNUAL DEATHS, INJURIES AND WORKDAYS LOST FOR UNCONTROLLED OIL-FIRED ELECTRICITY SYSTEMS ASSOCIATED WITH A 1,000-MEGAWATT POWERPLANT WITH A LOAD FACTOR OF 0.75[a]

	EXTRACTION			TRANSPORT[d]					TOTAL		
	ONSHORE	OFFSHORE	PROCESSING[c]	ONSHORE	OFFSHORE	IMPORT	CONVERSION[e]	TRANSMISSION	ONSHORE	OFFSHORE	IMPORT
DEATHS	0.21	0.21	0.08	0.05	0.05	0.05	0.010	NA	0.35	0.35	0.06
INJURIES	21	21	5.6	4.5	4.5	4.5	1.15	NA	32.3	32.3	5.7
WORKDAYS LOST	2,135	2,135	785	562	562	562	127.2	NA	3,609	3,609	689

a. Reference 1.

b. Based on injury rate and the number of man-hours worked in oil extraction.

c. Based on the total man-hours worked. Ibid., note 18.

d. Based on 1969 occupational health data and on the share of all oil needed to fuel a 1,000 MWe powerplant for 1 year.

e. One-half the combined deaths and permanent injuries are assumed to be fatal injuries. Permanent total disabilities are considered to represent 6,000 workdays lost, and other disabilities are estimated as 100 days lost.

The USGS offshore reporting system covers outer continental shelf oil and gas spills associated with platforms and rigs. Since 1971, operators have been required to report all incidents. Prior to 1971, reporting of incidents was spotty.

Several studies of risks and trends of oil spills have been conducted in order to provide a reliable statistical basis for policy formulation to prevent oil pollution.[36,37,38,39,40] GKY and Associates attempted to derive trends, based on data in both the PIRS and SPCC files.[36] A graphic representation of spill volume data contained in these files for 1971 through 1975 is shown in Figure 3.[36]

Analysis of the data for 1975 indicated that the spill rate for vessels was approximately 1 gallon spilled for every 10,000 gallons transported. Most spillage was associated with large spills. Both large and small spills occurred most frequently for vessels, onshore transportation (railroads and trucks), and onshore wells. Small spills also occurred frequently at storage facilities. The data also indicated that:

1. The largest number of transportation accidents are associated with vessels and pipelines (inland),

2. The largest number of non-transportation accidents are associated with onshore facilities (wells) in the vicinity of the Great Lakes and inland and offshore wells in the Coastal regions,

3. The ranking of sources with the largest number of incidents is: vessels, wells (on and offshore), and pipelines, and

4. Major spill volumes tend to derive from vessels, pipelines, and onshore wells.

Trend analysis was performed by comparing data for 1975 to that for the period from 1972 to 1975. Results indicated significant decreasing trends in small spills from vessels and bulk storage facilities except in the Great Lakes area, but an increase in large spills from vessels especially on the east and west coasts. However, care should be exercised in drawing conclusions from these results because the data base is small and covers only a short time span and because the consistency and accuracy with which spills are reported cannot be established.

A method has been described which attempts to determine the probability of a spill, the probable distribution of spill sizes, and the recurrence interval (the average period of time between two spills greater than or equal to a specific size).[37] This approach depends on availability of valid data; however such data generally have not been available. Data from the PIRS and SPCC data files may make this approach more useful.

A different approach was taken by Paulson et al in a risk analysis of large volume oil spills.[38] Their method is based on statistical analysis of the available data. With further development the method may lead to predictions of individual or total spillage.

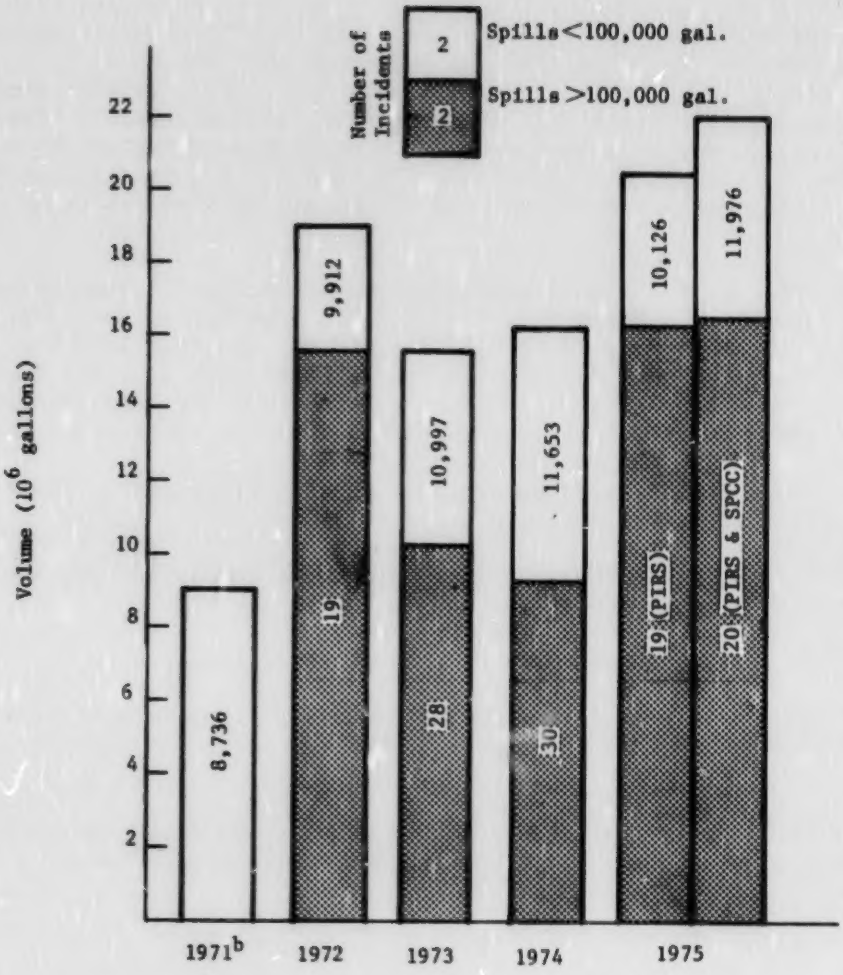

Figure 3. Spill volume per year.[a]

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a Reference 36

b Data on large spills not available

Table 23 provides an estimate of the relative contribution of various sources to oil in the ocean.[41] Much of this oil enters the water as a result of normal operations rather than because of accidents.

Data on oil spills show that the quantity of oil spilled varies with the source and type of accident. Most spills are small with large spills occurring only infrequently. Data for 1971 and 1972 show that one spill greater than one million barrels occurred in each year (Table 24).[42] Analysis of 36 major oil spills indicated that three-fourths involved vessels (Figure 4).[43] The oil spilled may be either crude or a petroleum product. The petroleum products can be further subdivided into light and residual oil fractions. An analysis of 35 incidents showed that 80% of the oil spilled was crude oil (Figure 5).[43]

Shipping is the largest single source of oil pollution. A summary of data collected from Lloyd's Weekly Casualty Reports, the U.S. Coast Guard, and oil companies for tankships in excess of 3,000 dwt is given in Table 25.[4] The information summarizes 3,183 accidents from 1969 through 1973 and includes type of accident, deaths and injuries, and resulting overflow. An analysis of 47 tankship losses of over 10,000 dwt (Table 26)[4] from the table shows that:

1. Collisions and groundings account for about half of the accidents and approximately 44% of the outflow.
2. Structural failures, which account for 16% of the accidents, account for more than one-third of the outflow.
3. Less than one-fourth of the accidents occur at sea, and
4. Approximately 11% of the tanker accidents resulting in out outflow also result in loss of the tanker. These accidents account for 81% of the oil outflow.

Characteristics of major spills which occurred prior to 1970 are contained in Table 27.[43] Generally, the following conclusions can be reached about past major spills:[43]

1. The source of the spill was likely to be a tanker,
2. Crude or residual fuel oil cargoes were involved in 90% of the spills.
3. The size of the spill was greater than 5,000 bbl, 75% of the time, with a median size of 25,000 bbl,
4. The spill usually occurred within 10 miles of shore,
5. The duration of a spill incident was usually more than five days, with a median of 17 days duration,

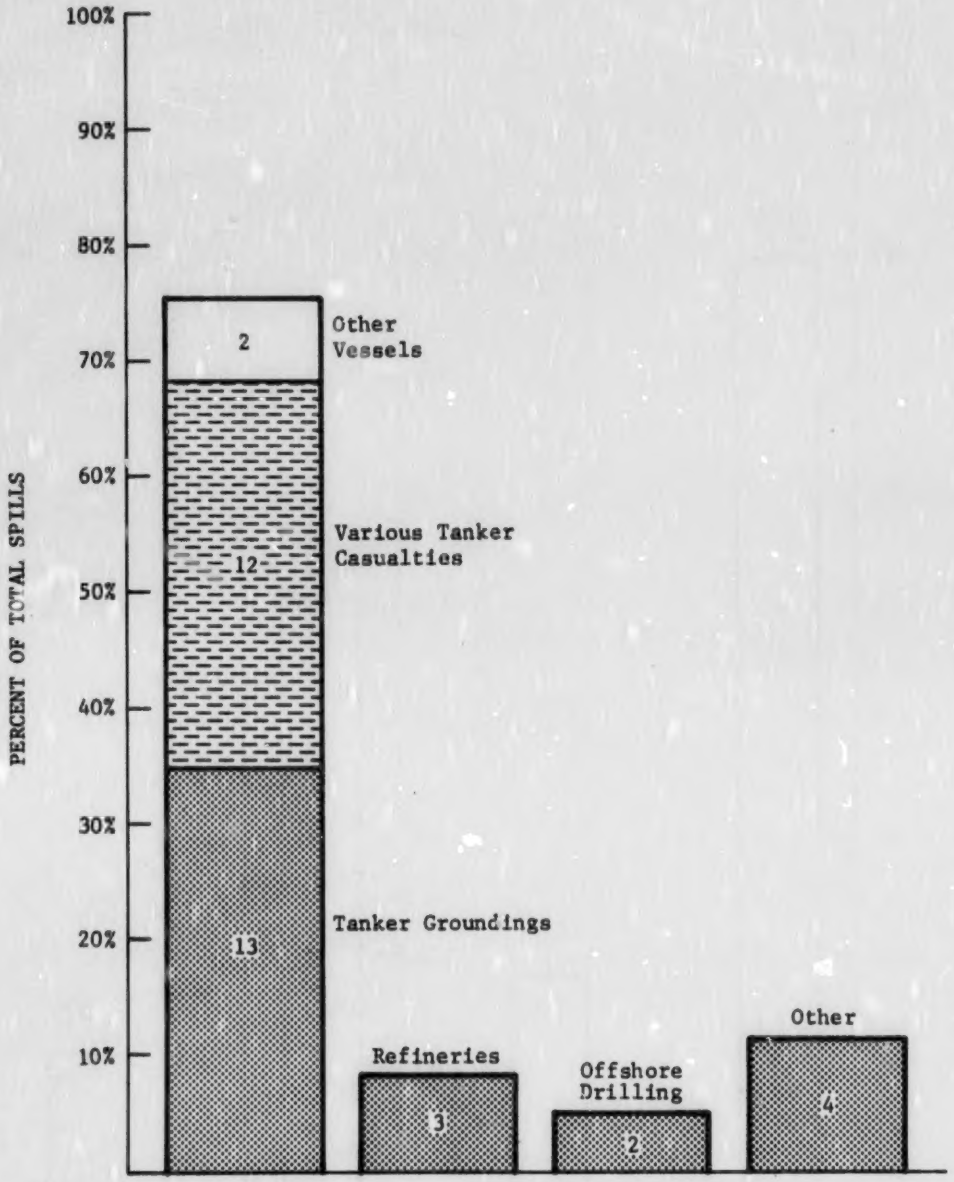

Figure 4. Source of spill. Data from 36 incidents, 1956 to 1969.[a]

[a] Reference 43

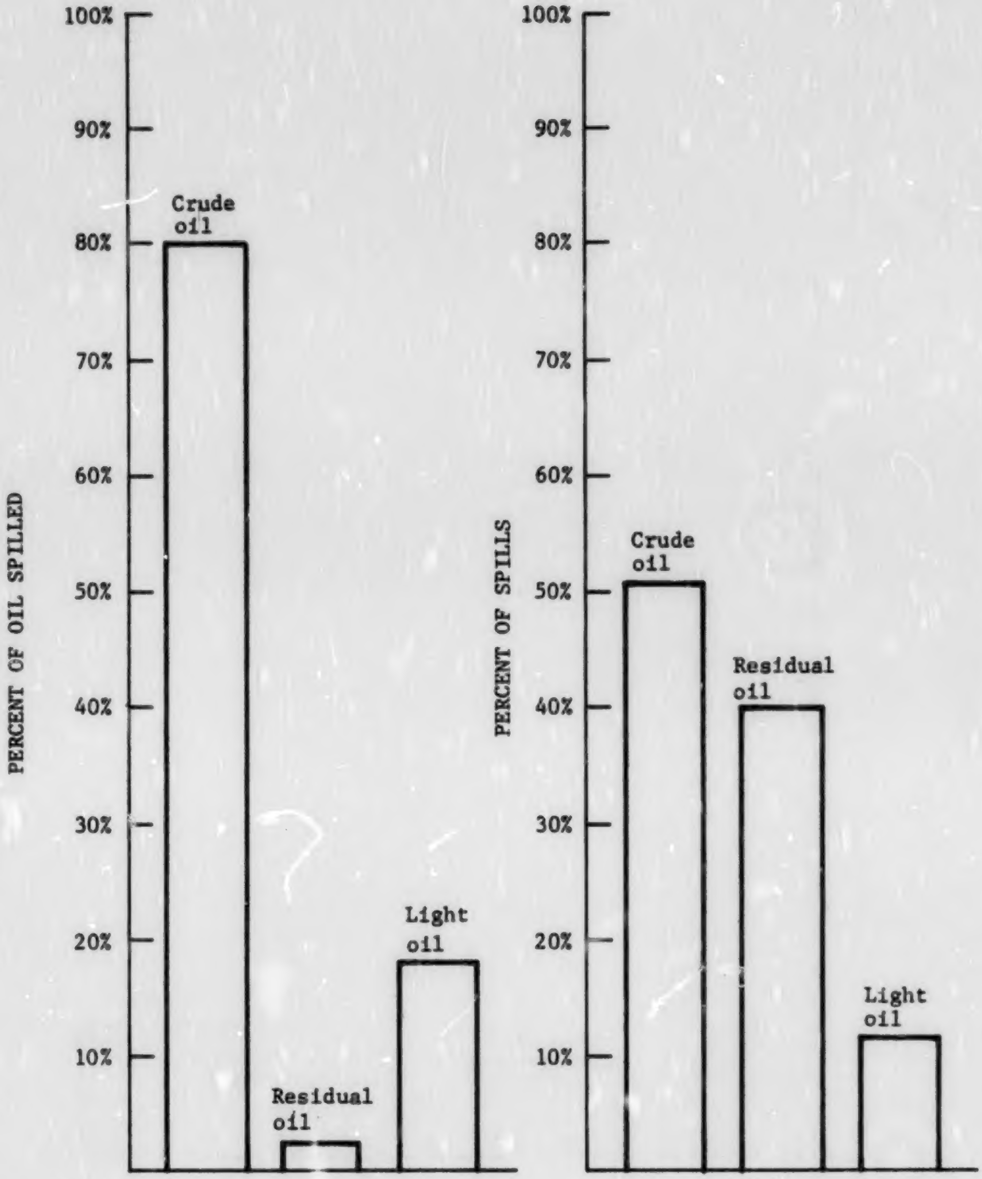

Figure 5. Composition of material spilled.[a]

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[a] Reference 43.

TABLE 23. CONTRIBUTIONS OF VARIOUS SOURCES TO OIL IN THE OCEANS[a]

SOURCE	ESTIMATED CONTRIBUTION (TONS/YR)	(%)
TRANSPORTATION TANKERS, DRY DOCKING, TERMINAL OPERATION, BILGES, ACCIDENTS	2,350,000	34.9
COASTAL REFINERIES, MUNICIPAL AND INDUSTRIAL WASTE	875,000	13.0
OFFSHORE OIL PRODUCTIONS	87,500	1.3
RIVER AND URBAN RUNOFF	2,100,000	31.2
ATMOSPHERIC FALLOUT	660,000	9.8
NATURAL SEEPS	660,000	9.8
TOTAL	6,732,500	100.0

[a] Reference 41

TABLE 24. NUMBER OF OIL SPILLS BY VOLUME AND SOURCE, 1971-1972[a]

SPILL VOLUME (BARRELS)

FACILITY	0-1	1-10	10-100	100-1,000	1,000-10,000	10,000-100,000	100,000-1,000,000	1,000,000-10,000,000
TERMINAL								
1971	384	247	458	282	77	19	7	1
1972	351	347	544	298	71	16	5	0
SHIP (OFFSHORE)								
1971	4	6	8	0	4	0	0	0
1972	15	2	10	3	0	0	1	1
PIPELINE								
1971	222	403	496	257	41	13	2	0
1972	15	24	61	61	32	7	3	0
PLATFORM								
1971	227	304	395	146	13	2	0	0
1972	431	784	728	244	20	4	0	0
TOTAL								
1971	837	960	1,357	685	135	34	9	1
1972	812	1,157	1,343	606	123	27	9	1

a. Reference 42.

TABLE 25. TANKSHIP ACCIDENTS, 1969-1973[a]

TYPE OF ACCIDENT	NO. OF ACCIDENTS	NO. OF ACCIDENTS RESULTING IN OUTFLOW (%)	OUTFLOW (LONG TONS)	NO. OF ACCIDENTS RESULTING IN TOTAL LOSS (%)	OUTFLOW (LONG TONS)	ACCIDENTS 1971-1973			LOCATION OF 452 ACCIDENTS				
						NO.	DEATHS	INJURIES	PIER	HARBOR	ENTRANCE	COASTAL	SEA
Breakdown	355	11 (2.4)	29,940	2 (3.9)	29,350	4	5	53	0	1	1	5	3
Collision	744	126 (27.9)	185,088	7 (13.7)	140,779	26	259	130	5	41	25	45	9
Explosion	104	31 (6.9)	94,803	11 (21.6)	88,780	33	46	47	5	4	0	6	15
Fire	197	17 (3.7)	2,935	1 (2.0)	1,250	14	34	10	10	2	0	1	4
Grounding	790	123 (27.2)	230,806	12 (23.5)	134,449	0	0	0	1	27	40	53	2
Ramming	473	46 (10.2)	13,645	0 (0)	0	0	0	0	18	15	5	4	2
Structural Failure	515	94 (20.8)	339,181	15 (29.4)	322,519	6	37	32	8	9	4	7	64
Other	5	4 (0.9)	54,911	3 (5.9)	54,790	0	0	0	1	0	0	2	1
Totals	3,183	452 (100)	951,317	51 (100)	771,917	83	381	178	48	99	75	123	98

a. Reference 4.

TABLE 26. ACCIDENT SEQUENCE FOR 47 TANKSHIP LOSSES FOR TANKSHIPS OVER 10,000 DEADWEIGHT TONS, 1969-1973[a]

ACCIDENT SEQUENCE	NUMBER	OIL OUTFLOW (LONG TONS)[b]	(BARRELS)
Breakdown-Structural Failure-Sink	1	16,350	123,933
Breakdown-Grounding Sink	1	13,000	98,540
Collision-Sink	2	4,138	31,365
Collision-Explosion/Fire-Sink	4	136,163	1,032,116
Explosion/Fire-Sink	12	90,030	682,427
Grounding-Explosion/Fire-Sink	1	2,500	18,950
Grounding-Sink	9	134,726	1,021,223
Flooding-Sink	2	54,669	414,391
Structural Failure-Grounding-Sink	1	40,000	303,200
Structure Failure-Sink	14	282,519	2,141,494
Total	47	774,095	5,867,640

[a] Reference 4

[b] Conversion factor: Long tons x 7.58 = Barrels

TABLE 27. MAJOR OIL-SPILL INCIDENTS-SIGNIFICANT CHARACTERISTICS (1956-1969)[a]

NAME	CAUSE OF SPILL	MATERIAL	VOLUME (BARRELS)	DISTANCE FROM SHORE (MILES)	EXTENT OF CONTAMINATION (MILES)	DISTANCE FROM PORT (MILES)	DURATION (DAYS)
Algol, tanker	Grounding	#6 F.O.	4,000	3	None	<10	21
Andron, tanker	Sinking	Crude	117,000			>50	
Anne Mildred Brovig, tanker	Collision	Crude	125,000				75
Argea Prima, tanker	Grounding	Crude	28,000		15		
USS Bach (DDE-470)	Grounding	#6 F.O.		<1	None	<10	23
Benedicte, tanker	Collision	Crude	14,000	13	Minor	10-25	13
Chryssi P. Goulandris, tanker		Crude	2,600	<1	Moderate	<10	
Dutch Coast Spill	Unknown	Residual	1,000		Moderate	10-25	
Esso Essen, tanker	Grounding	Crude	30,000	3	15		7
Fawley, refinery	Pumping	Crude		<1	Moderate	10	
General Colocotronis, tanker	Grounding	Crude	30,000	2	Moderate		60
Hamilton Trader, tanker	Collision	Residual	5,000		45		90
Hess Hustler, tank barge	Grounding	#6 F.O.	40	<1		25-50	5
Humboldt Bay, refinery	Hose Failure	Diesel	1,400				
Kenai Peninsula, tanker	Collision	Crude	1,000	<1	Minor	<10	2
Keo, tanker	Hull Failure	#4 F.O.	210,000	120	None	>50	
Martita, tanker	Collision	Bunker C	4,300	<1		<10	
Moron, refinery	Pumping	Crude	16,000	<1	6	<10	5
New Castle, power station	Leak	Residual	40	<1	Moderate	<10	
Ocean Eagle, tanker	Grounding	Crude	83,400	<1	16	<10	65
Palva, tanker	Grounding	Crude			5		
Pegasos, tanker	Hull Failure	Bunker C		270	None	>50	13
P. W. Thirtle, tanker	Grounding	Bunker C		2	Extensive	10-25	
R. C. Stoner, tanker	Grounding	Mixed	143,000	<1	Extensive	>50	10
Refinery Loading Site	Hose Failure	Crude	2,000	<1	25	<10	55
Robert L. Polling, tank barge	Collision	#2 F.O.	4,700	<1	13		1
Santa Barbara, platform	Natural Faults	Crude	100,000	6	40	<10	100
Seagate, tanker	Grounding	Residual				45	
Seewarren, storage tank	Tank Failure	Crude	200,000	<1		<10	
Ship Shoal, drilling rig	Storm Shifting	Crude	2,400	6	None		3

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[a] Reference 43 (Vol. II, P. 244).

TABLE 27. Continued

NAME	CAUSE OF SPILL	MATERIAL	VOLUME (BARRELS)	DISTANCE FROM SHORE (MILES)	EXTENT OF CONTAMINATION (MILES)	DISTANCE FROM PORT (MILES)	DURATION (DAYS)
USS Shangri-La (CVA-38)	Pumping	NSFO	200		Moderate		3
Tampico, tanker	Grounding	Diesel	60,000	<1	3	>50	
Tim, tank barge	Sinking	#6 F.O.	7,000	<1	Moderate		13
Torrey Canyon, tanker	Grounding	Crude	700,000	15	242	25	30
Waikiki Beach	Unknown	Bunker C		<1	7	<10	4
Waterford Beach	Unknown	#6 F.O.		<1	20		10
Witwater, tanker	Hull Failure	Mixed	15,000	<1	Extensive	<10	
World Glory, tanker	Hull Failure	Crude	322,000	40	None	>50	20

6. The shoreline threatened was at least partially recreational for 80% of the spills, with a median of four miles contaminated, and

7. Three-quarters of the spills occurred within 25 miles of a port.

Blowouts and well-casing ruptures are other potential sources of major oil spills. A blowout is the uncontrolled flow of oil or gas from a well bore. A National Petroleum Council survey showed that between 1960 and 1970 there were 106 blowouts in the drilling of 273,000 wells in eight major oil-producing states.

The survey figures of 106 blowouts may not accurately summarize the situation. A blowout is considered to be any of the conditions ranging from potential loss of well control to the catastrophic blowout resulting in fire and loss of the rig. Potential intermittent loss of control (e.g., 1-hour loss) are occurrences which are generally unreported and probably relatively common. Oil drilling (production) operations in southern Louisiana, for example, operate on the borderline of loss of control. In this area there is a fine balance between circulation rate and loss of well control, with the line being crossed in both directions during the course of operations. The catastrophic occurrence is often recorded because reporting to a responsible regulatory authority or an insurance company may be required. The figures for blowouts may therefore belong to the severe category only. It is possible, however,that the relative number of blowouts in relation to wells drilled is decreasing with development of well control technology.

Blowouts have also been related to fires, such as the recent offshore rig accident in the Gulf of Mexico. The best known of the major polluting blowouts occurred in the Santa Barbara (California) Channel, 6.5 miles from shore, in 1969. Uncontrolled flow lasted from January 28 to February 7. After cementing of the well, seepage continued at a rate of approximately 300 bbl per day until September 1969. Seepage then was reduced, by grouting, to approximately 10 bbl per day.

Well casing is a cemented steel sleeve implanted in the well walls. Its purpose is to support the well walls and to prevent intrusion of oil, brines, and mud into the subsurface geologic structure. The Santa Barbara accident showed that the casing was shallow, extending 238 feet below the sea floor for the 3,313 foot well. When the well was shut off at the top, fluid pressure built up in the well and blew out just below the bottom of the casing.

Oil spill control regulations, environmental awareness, and technological advances have combined to reduce the number of blowouts. Blowout preventer stacks and cementing of steel casing into the bore hole reduce the frequency of blowouts. The blowout preventer stack is mounted at the top of the casing and consists of a series of manual or automatic valves which can close off the well in the event of loss of control.

When oil spills do occur, several methods can be used to contain and remove the oil. For example, containment and recovery can be accomplished by mechanical methods and sorbent materials, the latter presenting logistical problems of disposal and collection. Mechanically, booms may be used to contain the oil by encircling it and sweeping it to a collection point or to funnel oil in a "V" configuration to skimmers mounted on barges. This is effective in protected areas such as harbors. Booms are also used to prevent oil from entering marinas and tributaries and to protect boats and other property. Air barriers also have been used effectively in harbors or calm inland waters. Containment of oceanfloor seeps is accomplished by means of hoods connected to surface containers with flexible hosing. Another method of reducing the amount of oil entering the marine environment is controlled burning while relief wells are drilled to kill the formation feeding the producing wells.

Three methods of recovering the oil once it is contained are oil adhesion, open skimmer, and floating-surface skimmer. None of these are satisfactory in heavy seas.

Many treatment processes can be used. Among these are combustion, sinking, and dispersants. The combustion technique has been attempted with little success and may have detrimental environmental consequences such as sediment contamination by hydrocarbon residues.[44] If used immediately after a spill, there is danger to personnel and property, while if tried after weathering, ignition and sustained combustion become difficult due to loss of crude-oil volatiles. The addition of materials which sink the oil is not widely used because this transfers the problem to the bottom environment rather than solving the problem.[43,44] Dispersants are not widely used because they may be toxic to marine life especially in enclosed or shallow waters.

4.2.1.2 Effects--

The effects of an oil spill depend on a number of variables associated with the spill. These include the volume of the spill, the composition of the spilled oil, the effects of weathering, marine transport (e.g., dispersion, trajectory), existing ecosystems, toxicity, physiography, and cleanup operations (duration, type, extent).

Toxicity is related to the composition of the spilled oil. Low boiling, saturated hydrocarbons can produce anesthesia and narcosis in low concentrations. They also can cause cell damage and death in lower animals at higher concentrations. Low boiling aromatic hydrocarbons (e.g., benzene, toluene, and xylene) are abundant in all oils and most oil products and are that most immediately toxic fraction.[45] Low-boiling aromatics are more water soluble than the saturates and can kill marine organisms either by direct contact or through contact in dilute solution. Other components of crude oils which are both soluble in water and toxic are cresols, xylenols, naphthols, and quinoline. A summary of toxicity data for various organisms is contained in Table 28.[46]

The toxicity of oils is greatest for the lightest fractions (Table 29).[47] Refined oils containing a greater percentage of low boiling substances are more toxic than crude oil.

TABLE 28. SUMMARY OF TOXICITY DATA[a]

CLASS OR ORGANISM	ESTIMATED TYPICAL TOXICITY RANGES (ppm) FOR VARIOUS SUBSTANCES SAD[b]	#2 FUEL OIL/KEROSENE	FRESH CRUDE	WEATHERED CRUDE
Flora	10-100	50-500	$10^4 - 10^5$	Coating more significant than toxicity
Finfish	5-50	25-250	$10^4 - 10^5$	
Larvae	0.1-1	0.5-5	$10^2 - 10^3$	
Pelagic Crustaceans	1-10	5-50	$10^3 - 10^4$	
Gastropods	10-100	50-500	$10^4 - 10^5$	
Bivalves	5-50	25-250	$10^4 - 10^5$	
Benthic Crustaceans	1-10	5-50	$10^3 - 10^4$	
Other Benthic Invertebrates	1-10	5-50	$10^3 - 10^4$	

[a] Reference 46

[b] Soluble aromatic derivatives (aromatics and napthenoaromatics).

TABLE 29. VARIATION IN BIOLOGIC EFFECTS OF OIL WITH TYPE OF OIL[a]

TYPE OF OIL IN ORDER OF INCREASING BIOLOGIC EFFECT	TYPE OF ORGANISM IN ORDER OF INCREASING BIOLOGIC EFFECT
Crude Oil	Mammals, Finfish, Plankton, Benthos, Birds
No. 6 Fuel Oil	Mammals, Finfish, Plankton, Benthos, Birds
No. 2 Fuel Oil	Mammals, Birds, Finfish, Plankton, Benthos

[a] Reference 47

The higher toxicity of refined oils is illustrated by the spill of No. 2 distillate oil which occurred at West Falmouth, Massachusetts in 1969. This spill produced an immediate kill of fish, clams, snails, crabs, lobsters, worms, and other invertebrates. Oil was incorporated into sediments and continued to inhibit repopulation nine months after the spill.[48]

The effects of spills in a estuarine or marine environments can be summarized as follows:

1. Direct lethal toxicity - Dissolved aromatic hydrocarbon derivatives can disrupt membrane activity in crustaceans, burrowing organisms, and to a lesser extent in fish and mollusks, leading directly to organism death.[46]

2. Disruption of physiological and behavioral activity - Chemical communication can be inhibited leasing to abnormal feeding, reproduction, orientation, and migration of many marine organisms.[46] This could result from contamination by weathered crude or No. 2 fuel oil. For most spills, this effect would persist for only a few hours if it occurred at all. However, in the rare instance in which a highly toxic product such as No. 2 fuel oil is spilled under unusually adverse sea conditions so that vertical mixing occurs and the sediments become saturated with the oil, this effect could persist for several months or even for a year or more.[49]

3. Direct coating by oil - Oil may smother or physically inhibit activities such as feeding and locomotion. Sessile organisms are most susceptible to coating.

4. Incorporation of hydrocarbons in food chains - Polynuclear aromatic hydrocarbons, some of which are carcinogenic, are generally present in oils in concentrations of a few parts per million. These compounds are easily absorbed and concentrated by marine animals. However, marine animals quickly depurate these hydrocarbons once they have been removed from exposure to the oil.[50,51] Finfish and filter feeding organisms such as clams and oysters concentrate hydrocarbons in body tissues creating an objectionable taste.

5. Habitat changes - Alteration of the physical-chemical environment, especially in the sediment, will cause shifts in species composition, relative abundance, and areal distribution. The degree to which oil will contaminate sediments is a function of the absorption capability of the sediment, depth of water, vertical mixing, and state to which the slick has weathered and become more dense.

In addition to these effects, a significant number of sea birds can be killed by an oil spill. Between 40,000 and 100,000 birds were killed as a result of the Torrey Canyon spill,[52] 7,000 in the San Francisco Bay spill,[53] and 3,700 in the Santa Barbara blowout.[54] The principal effect of an oil slick on birds is physical coating. Birds become coated because they may not recognize an oil slick until they cannot avoid contact. It is felt that the swimming species are more endangered by coating than are aerial species, who rarely come in contact with oil regardless of its location.[49] Birds are warm-blooded with their feathers serving as insulation. In addition, they have to be waterproof. A swimming bird encountering oil will dive, generally resurfacing in the oil. The oil mats the insulating feathers presenting the possibility of the bird freezing to death or dying from disease resulting from body heat loss. A further effect of the matting is to disturb the buoyancy, disrupting the feeding and swimming capability of the bird, both of which can cause death.[55] Birds also die from ingestion of oil as a result of preening or eating oil contaminated food.

The length of time it takes for a marine or estuarine ecosystem to recover from an oil spill has not been established. Although some feel that there are few long term effects,[47] others feel that long term ecosystem disruption can occur.[45] However, it is apparent that the time required for recovery depends on many factors including the volume of oil spilled, the kind of oil spilled, meteorological conditions, and cleanup measures. Table 30 summarizes the biologic recovery observed after several oil spills.[47] A summary of the effects of oil on selected species is shown in Table 31.[56]

The toxicity of oil and the persistance of its effects depend, in part, on weathering which is the alteration of oil by evaporation, dissolution, microbial decomposition, and chemical oxidation. Evaporation and dissolution lead to rapid depletion (2 - 4 days) of the low-boiling, highly toxic fractions. Microbial and chemical oxidation of most higher boiling fractions is a relatively slow process and may take several years.[46,57]

Persistence times of oil have been estimated based on observations following a number of spills. One estimate for persistance of weathered oil is shown in Figure 6.[56]

Persistence in the marine environment is related to transport of oil after a spill. The movement of an oil spill in the marine environment is dependent upon wind, wave action, currents, and turbulence. Poor weather conditions, for example, can cause wide dispersal of oil before control activities can be effected. Turbulence, as well as some chemical clean-up methods, can transport oil to the sediments where it can persist for a significant time. The oil reduces cohesion of the sediment which then gives rise to significant littoral drift, moving the oil to areas not previously affected by the spill.[44]

Oil spilled near a shore can leave a visible coating on rocks, sand, and marsh flora. The extent of the effects will depend upon the use of the shore, i.e., whether it is industrial, residential, recreational land, or salt marsh or other wetlands. Recreation shoreline used as a beach cannot be used until the oil is removed.

An examination of 21 oil spill incidents indicated that 80% occurred within 10 miles of shore with a median duration of 17 days. Based upon an apparent drift rate of 3.3% of the average wind velocity (assumed 15 knot wind) it was indicated that oil could reach the shore in less than one day in 80% of the cases. A further analysis of the data indicated that less than 20 miles

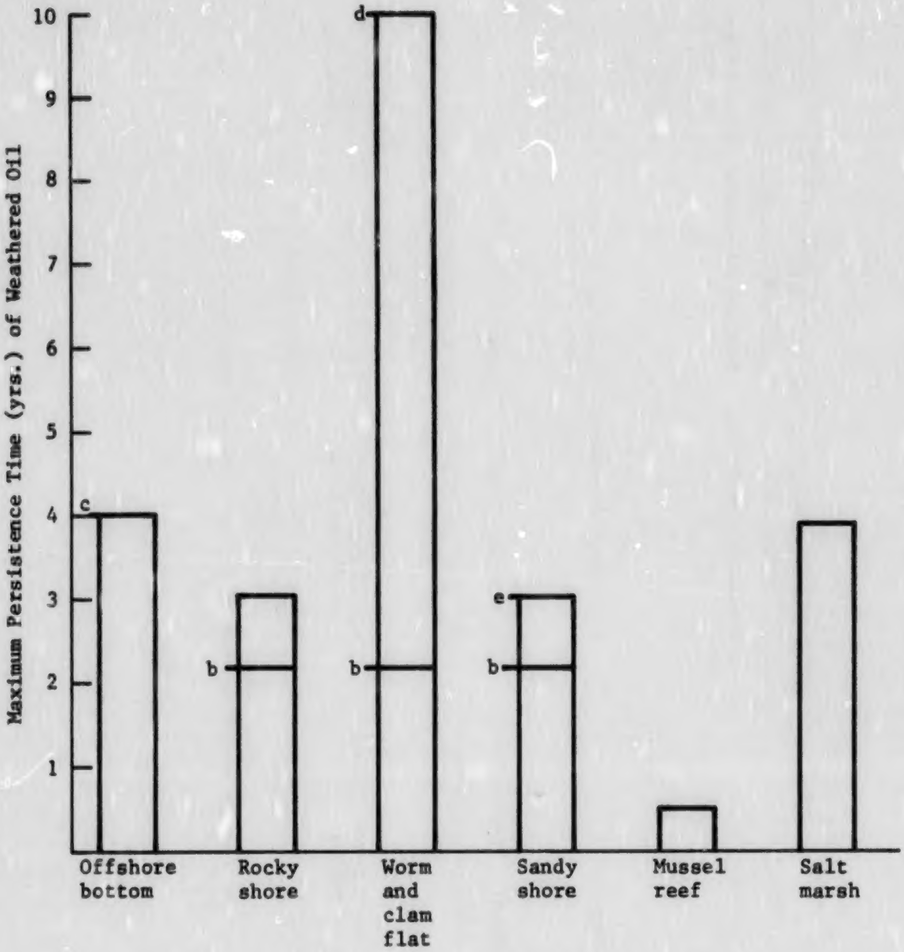

Figure 6.[a] Observed persistence of petroleum substances in various marine habitats following actual oil spills.[f]

[a] Reference 56

[b] Analytical determination of oil (Scarratt & Zitko, 1972).

[c] Estimate after 2 years; analytical methods; used #2 fuel oil (Blumer & Sass, 1973).

[d] Visual observation and analytical; JP-5 and #2 fuel oil (Shenton, 1973).

[e] Gas-liquid chromatography analysis (Spooner, 1971).

[f] Maximum times shown do not necessarily imply complete removal of oil, but may represent an estimate of persistence or termination of study.

TABLE 30. BIOLOGIC RECOVERY FOLLOWING OIL SPILLS[a]

INCIDENT	OIL	STATE OF BIOLOGIC COMMUNITIES, TIME AFTER SPILL IMMEDIATELY	ONE-HALF YEAR	ONE YEAR	LONGER
S/S Tampico Maru	No. 2 fuel oil	Extensive damage	Repopulation beginning	Many healthy species	After 3 years, recovery nearly complete - slightly different from original
West Falmouth	No. 2 fuel oil	Extensive	No evidence of recovery	Slight repopulation, some localities	After 2 years, recovery under way in most areas
S/S Arrow	No. 6 fuel oil	Slight to considerable	Area appears normal	Appears normal	
San Francisco Bay	No. 6 fuel oil	Slight to considerable	Population reduced on Doxbury Reef	Population somewhat reduced - repopulation proceeding at normal rate	
S/S Torrey Canyon	Kuwait crude	Slight (after applying detergents)	Repopulation under way in some areas	Repopulation under way	Repopulation continuing
Santa Barbara	California crude	Slight	Communities have normal numbers - appear healthy	Appears normal	

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[a] Reference 47

TABLE 31. EFFECTS OF OIL ON SELECTED SPECIES[a,b]

SPECIES	COMMON NAME	LETHAL	SUBLETHAL	COATING	UPTAKE AND TAINTING	HABITAT CHANGE
Birds						
Rissa tridactyla	Kittiwake			x		
Fishes						
Alosa spp.	Alewife	x				
Clupea harengus	Herring	x				
Fundulus heteroclitus	Mummichog	x				
Gadus morhua	Atlantic cod	x				
Micropogon undulatus	Croaker		x			
Morona saxatilis	Striped bass		x			
Pseudopleuronectes americanus	Winter flounder	x				
Crustaceans						
Acartia spp.	Zooplankter	x				
Ampelisca vadorum	Amphipod	x				x
Balanus balanoides	Acorn barnacle	x				
Calanus spp.	Zooplankter	x			x	
Crangon spp.	Shrimp	x				
Emerita spp.	Mole crab	x				
Homarus amenicanus	American lobster	x	x			
Paqurus longicarpus	Hermit crab	x			x	
Pandalus spp.	Shrimp	x				
Mollusks						
Aequipecten spp.	Scallop	x	x		x	
Crassotrea spp.	Virginia oyster	x	x		x	
Donax spp.	Coquina clam	x				
Mercenaria mercenaria	Northern quahog	x				
Modiolus spp.	Horse mussel		x		x	
Mya arenia	Soft shell clam	x			x	x
Mytdus edufis	Edible mussel	x	x	x	x	

(Continued)

TABLE 31. (Continued)

SPECIES	COMMON NAME	LETHAL	SUBLETHAL	COATING	UPTAKE AND TAINTING	HABITAT CHANGE
Mollusks (Continued)						
Nittorina hittorea and *spp.*	Periwinkle	x	x	x		
Nassarius obsoletus	Common mud snail		x			
Thais lapillus	Dog whelk	x	x			
Worms						
Aranicola marina	Lugworm	x	x			x
Nereis virens	Clam worm	x				
Streblospio benedicti	Polychaete	x				
Other animals						
Asterias vulgaris	Starfish				x	
Strongylocentrotus droebachiensis	Sea urchin	x			x	
Plants						
Juncus gerardi	Marsh rushes	x			x	
Spartina alterniflora	Marsh grasses	x			x	
Spartina patens	Cord grass	x				
Laminaria spp.	Kelp	x				

[a] Reference 56

[b] Does not list all species for which data have been reported. Rather, an x represents reported data for those species which were selected for special consideration. An x indicates that some data, regardless of number, have been reported.

of shoreline was affected in 80% of the spills with a median of 3-4 miles. An analysis of 23 spills showed that recreational shoreline was affected in 85% of the spills, with residential and industrial each affected in 45% of the incidents. Multiple use accounts for the overlap in percentages. Thus, it is likely that in the event of a spill, recreational shoreline will be affected within one day.

A spill of crude oil also presents a fire hazard. The hazard generally diminishes with time with the loss of the volatile fractions. Spills of light, refined products (e.g., gasoline) also are a fire hazard; however, heavy fractions (e.g., No. 6 fuel oil) are much less likely to catch fire.

A fresh spill of crude oil at sea can be easily ignited and may flash to the tanker resulting in a further toll of property loss and injury with subsequent involvement of rescue men and equipment. However, the hazard is generally more acute on land as the spill occurs around a well, refinery units, and storage tanks. Electrical machinery, such as pumps, are located in and around these areas which increase the likelihood of a spilled oil fire as a result of an electrical spark. This has occurred in tank farm areas causing extensive damage.

Inland water spills have accounted for some of the largest expenditures of public funds for inland clean-up. For example, flooding of a storage lagoon near Douglasville, Pennsylvania caused by Hurricane Agnes resulted in release of 6 million gallons of waste oil to the Schuylkill River. Clean-up costs were nearly $6 million. Similarly, more than $8 million has been spent to clean up shorefronts, boats, marshes, and property along 80 miles of the St. Lawrence River because of a spill of No. 6 fuel oil in June 1976. Clean-up operations are still continuing.

Numerous adverse effects may result from an oil spill on inland waters. Vegetation may be damaged and benthic organisms may show an increase in heavy metal and hydrocarbon concentrations. Marshes, wildlife refuges, and water fowl (e.g., Canadian geese, ducks) may be damaged. The spilled oil may also threaten sources of potable water, irrigation supplies, and industrial water supplies.

Oil spills on land are few in number and account for small volumes when compared with spills on water. The blowout is the major source during drilling. Most of these occurred with high-pressure gas wells as opposed to oil wells.

The major problem associated with a blowout is seepage into and subsequent contamination of aquifers used for drinking and other consumptive purposes. Oil companies have controlled blowouts through the use of blowout prevention devices (BOP's) and through training of their field crews.

Accidental releases from refineries to land are generally in the form of oil or oil-contaminated water resulting from leaks, spills, and ruptures. Regulation and good housekeeping practices dictate that containment methods such as diking be used around equipment. This localizes the spill to the processing and storage areas.

4.2.2 Tanker Accidents

Tanker accidents result not only in oil spills but also in injury, death, and loss of property. The United States Coast Guard, Office of Merchant Marine Safety, analyzed data from 3,715 worldwide tankship accidents from 1969 through 1973.[4] Table 25 contains a summary relating death and injury to various types of accidents. The data indicate that 18.4% of the accidents involved death or injury. A total of 38 deaths occurred during a three year period with 2.14 deaths for every injury. Approximately 31% of the accidents resulted from collision. Those accidents accounted for 68% of the deaths and 73% of the injuries. Explosions were involved in 40% of the accidents involving death or injury but resulted in only 12% of the deaths and 26% of the injuries.

Data also were presented which indicate the extent of damage to the ships involved (Table 32).[4] Of the 3,183 accidents, 73% caused only minor damage, while 15% caused no damage. Only 1.6% of the accidents resulted in total loss. The actual dollar amount of the damage or losses depends on repair or replacement costs, lost business revenues, increased insurance premiums, and other factors for which no data were available.

The accident sequence for 47 of the 51 total losses is shown in Table 26. More than 1/3 of the total losses were caused by structural failure and accounted for 44% of the oil outflow. Causes for loss of structural integrity for these 47 accidents are shown in Table 33.[4]

4.2.3 Offshore Rig Accidents

There are four basic types of offshore rigs used in drilling for oil and gas: submersibles, jack-ups, semi-submersibles, and floaters. A study analyzed offshore rig casualties, on an industry-wide basis, for the period 1955-1976.[58]

The current fleet of operating rigs number more than 340 with a total estimated value of over $6 billion. Each year more than 2% of the value of offshore rigs is lost due to accidental damage. The leading cause of rig loss is rig moves during stormy weather. Since 1955 there have been 100 accidents, each with losses in excess of $500,000, resulting in documented losses totalling $438,850,000. These 100 accidents accounted for 121 fatalities. Of these, jack-ups were involved in the most (61 accidents), accounting for almost 64% of all damage losses and 33% of the total fatalities. Floaters, while accounting for only 6% of the damage costs, were involved in 35% of the fatalities (42), more than from any other type of rig. Since 1955 the casualty ratio of rigs damaged to rigs operated has been 3.2%. The offshore drilling industry operated 3,255 rig-years with a total loss of 43. The fatality rate for offshore drilling has been estimated at 1 death/340,000 man-days, which is lower than the onshore construction industry rate.

Mobile drilling rig accidents are of two general types. The first is the type related to the industrial nature of the business. The second is a result of the marine environment. Among the first type, the most disastrous accident is the blowout, which can affect the rig and its occupants in several ways.

TABLE 32. EXTENT OF TANKSHIP LOSS OR DAMAGE 1969-1973[a]

TYPE OF INVOLVEMENT	TOTAL LOSS	HEAVY DAMAGE	LIGHT DAMAGE	NO DAMAGE	DAMAGE UNKNOWN
Breakdown	2	16	197	131	9
Collision	7	64	570	78	25
Explosion	11	30	52	10	1
Fire	1	26	149	14	7
Grounding	12	63	487	206	22
Ramming	0	23	412	35	3
Structural Failure	15	39	445	2	14
Other	3	1	1	0	0
TOTAL	51	262	2,313	476	81

[a] Reference 4

TABLE 33. DESCRIPTION OF LOSS OF STRUCTURAL INTEGRITY FOR 47 TANKSHIP LOSSES FOR TANKSHIPS OVER 10,000 DEADWEIGHT TONS, 1969-1973[a]

DESCRIPTION	NUMBER	OIL OUTFLOW (LONG TONS)
A. Loss of structural integrity of hull caused primarily by external forces or where local material conditions deteriorated. No explosion or fire was associated with the accident. These may be broken down into:		
1. Structural failure of main hull girder from excess bending or shear loading	12	243,619
2. Local structural failure of hull envelope		
a. Failure of hull penetration	2	36,750
b. Local hull plating failure	2	39,169
c. Unknown local structure failure	1	34,000
3. Hull damage caused by collision or grounding		
a. Collision	2	4,138
b. Grounding	11	187,726
Subtotal	30	545,402
B. Loss of structural integrity from damage caused primarily by explosion or fire or where explosion or fire contributed to loss of structural integrity. These may be broken down into:		
1. Explosion or fire initiated in own ship cargo tanks	12	90,030
2. Explosion or fire set off by vessel collision or grounding		
a. Collision	4	136,163
b. Grounding	1	2,500
Subtotal	17	228,693

[a] Reference 4

Should the gas or product ignite after a blowout, the drilling rig could easily catch fire resulting in total destruction. A flowout around a subsea wellhead, for example, could create sufficient aeration of the water to alter water density resulting in the vessel sinking. An effect on jack-ups or any design permanently anchored to the bottom, would be the scouring around mats, legs, or other bottom supports, due to escaping gas, which could cause foundation failure and subsequent rig damage. Of the 100 major accidents mentioned, 32% were related to industrial operations and accounted for $115.65 million (26%) of the total documented losses.

The second type of accident, resulting from the marine environment, accounted for 68% of the accidents. These resulted from moving of the rigs and/or storms. Forty of the major accidents occurred while the rigs were being moved. Of these, 35 involved jack-ups. Accidents involving moving of rigs accounted for losses of $123.8 million (28% of the total). The other 28 major accidents were storm related in which damage losses approximated $199.4 million (45% of the total). The industry and government agencies are attempting to reduce these types of accidents through improved design standards and personnel training programs.

4.2.4 Pipeline Accidents

The hazards associated with the pipeline accident include fire and explosion with resulting injury and/or loss of life, in addition to oil spill damage.

Liquid pipeline accidents caused approximately $3.2 million in property damage, the loss of 7 lives, 15 injuries, and the loss of over 319,000 barrels of commodity during 1975. A summary of pipeline accidents for 1975 is shown in Table 34.[59] A breakdown of accidents in terms of the commodity involved is shown in Table 35.[59] It should be noted that of the commodities lost as a result of accident, 45.1% was crude oil, 28.3% gasoline, and 21.5% liquified petroleum gas (LPG). Accidents involving LPG accounted for 86% of the deaths and 87% of the injuries.*

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* Injury and fatality statistics are always subject to discrepancies due to nonuniform or incomplete reporting. Statistics quoted in this section come from the Department of Transportation (DOT) and are based on DOT Form 7000-1 filed during the year 1975. The American Petroleum Institute (API) also has published data for 1975 based on information collected from 137 oil and gas companies and their subsidiaries. The API data are for the entire industry and are further divided by function (e.g., exploration and production, drilling, pipeline-crude and products). Comparison of the appropriate API and DOT data for pipeline (crude and liquid respectively) shows significant differences between the two sets of data:

	API	DOT
Injuries (lost time)	754	15 employee and non-employee
Fatalities	6 4	7 employee and non-employee

The API fatalities include tank truck accidents while the DOT figures apparently do not. The two API estimates of fatalities were obtained from separate sources. (API data are quoted in Section 4.2.)

TABLE 34. LIQUID PIPELINE ACCIDENT SUMMARY - JANUARY 1, 1975 THROUGH DECEMBER 31, 1975[a]

CAUSE OF ACCIDENT OPERATION ACCIDENTS	NO. OF ACCIDENTS	PERCENT OF TOTAL	DEATHS		INJURIES	
			CARRIER EMPLOYEES	NON EMPLOYEES	CARRIER EMPLOYEES	NON EMPLOYEES
Equipment Rupturing Line	75	28.6	0	0	0	1
Corrosion - External	57[b]	22.4	0	0	0	0
Equipment Failure	27	10.6	3	0	3	0
Incorrect Operation by Carrier Personnel	22[c]	8.6	0	0	0	0
Corrosion - Internal	16[b]	5.9	0	0	0	0
Defective Pipe Seam[h]	19[c]	5.9	0	0	0	0
Defective Girth Weld	5	2.0	0	0	0	0
Failure of Previously Damaged Pipe[i]	4	1.6	0	4	0	9
Vandalism	4	1.6	0	0	0	0
Failure of Previous Weld Repair	2	0.7	0	0	0	0
Lightning[k]	2	0.7	0	0	0	0
Miscellaneous	29	11.4	0	0	0	2
Total	255	100.0	3	4	3	12

(continued)

TABLE 34 (continued)

PROPERTY DAMAGE ($)			LOSS OF COMMODITY (BARRELS)	NUMBER OF ACCIDENTS BY YEAR OF INSTALLATION							
CARRIER	OTHER	TOTAL		BEFORE 1920	1920–1929	1930–1939	1940–1949	1950–1959	1960–1969	1970–1975	NOT REPORTED
$ 375,110	$266,751	$ 641,681	83,724	3	9	3	19	14	21	3	1
89,931	25,850	115,781	37,073	2	10	17	14	9	3	1	1
534,010	9,081	543,091	20,981	0	0	2	1	2	10	8	4
654,705	128,150	782,855	26,619	0	1	3	3	1	8	5	1
2,890	2,550	5,440	2,853	0	6	0	2	2	6	0	0
2,259	12,650	14,909	61,570	0	2	3	4	2	7	1	0
4,150	2,015	6,165	30,131	0	0	3	0	1	1	0	0
20,260	363,000	383,260	31,665	0	0	1	0	1	1	1	0
3,505	15	3,520	884	0	0	1	2	0	1	0	0
17,450	1,500	18,950	2,739	0	0	0	0	1	1	0	0
297,500	0	297,500	11,356	1	0	0	1	0	1	0	0
380,429	3,500	383,929	9,828	1	1	2	4	0	10	7	3
$2,382,199	$814,882	$3,197,081	319,423	7	29	35	50	33	71	26	10

(continued)

TABLE 34 (Continued)

[a] Reference 59

[b] One accident had both external and internal corrosion as the cause. Damages and loss of commodity are included in external corrosion caused group.

[c] Four accidents had both incorrect operation by carrier personnel and defective pipe seam as the cause. Damages and loss of commodity have been included in the incorrect operation by carrier personnel caused group.

[d] Accidents with property damages of $151,000; $130,650; $85,000; and $94,500.

[e] One accident - two deaths, three injuries, and $100,000 carrier property damages; another accident - one death and $300,000 carrier property damage; and another accident - $125,000 carrier property damage.

[f] One accident had total damages of $275,000.

[g] Two accidents had a commodity loss of 10,048 barrels (4,000 and 6,048).

[h] Three accidents had a commodity loss of 32,789 barrels (12,802; 10,000; and 9,987).

[i] One accident - four deaths and 25,500 barrels of commodity lost.

[j] One accident - nine injuries and $325,000 other property damages.

[k] One accident had two tanks (1917 and 1964) struck by lightning, destroyed by fire - $295,000 carrier property damage.

[l] One accident - one injury and $250,000 carrier property damage.

TABLE 35. PIPELINE ACCIDENT SUMMARY - BY COMMODITY INVOLVED[a]

COMMODITY	NO. OF ACCIDENTS	PERCENT OF TOTAL	LOSS IN BARRELS	PERCENT OF TOTAL	PROPERTY DAMAGE ($)			PERCENT OF TOTAL	DEATHS		INJURIES	
					CARRIER	OTHER	TOTAL		CARRIER EMPLOYEES	NON EMPLOYEES	CARRIER EMPLOYEES	NON EMPLOYEES
Crude Oil[b]	135	52.9	105,871	33.14	$1,293,923	$147,841	$1,441,764	45.1	1	0	0	1
Gasoline[c]	41	16.1	30,843	9.7	771,223	134,281	905,504	28.3	0	0	0	1
Fuel Oil	29	11.4	24,386	7.63	38,401	14,000	52,401	1.6	0	0	0	0
L.P.G.[d]	26	10.2	105,228	32.94	269,870	416,000	685,870	21.5	2	4	3	10
Jet Fuel	7	2.7	4,249	1.33	462	5,000	5,462	0.2	0	0	0	0
Natural Gasoline	7	2.7	21,475	6.73	916	94,210	95,126	2.96	0	0	0	0
Kerosene	4	1.6	25,030	7.84	6,919	2,150	9,069	0.28	0	0	0	0
Anhydrous Ammonia	3	1.2	1,311	0.41	10	1,000	1,010	0.03	0	0	0	0
Condensate	2	0.8	850	0.27	475	100	575	0.02	0	0	0	0
Transmix	1	0.4	180	0.01	0	300	300	0.01	0	0	0	0
TOTAL	255	100.0	319,423	100.00	$2,382,199	$814,882	$3,197,081	100.0	3	4	3	12

(continued)

TABLE 35 (Continued)

[a] Reference 59

[b] Accidents--$300,000 property damage and one carrier employee death; $151,000 property damage; $295,000 property damage and 11,356 barrels of commodity lost; 15,000 barrels of commodity lost; $250,000 property damage and one nonemployee injury; $85,000 property damage; and $125,100 property damage.

[c] Accidents--$59,431 property damage and 4,122 barrels of commodity lost and $775,000 property damage.

[d] Accidents--$58,000 property damage, four nonemployee deaths, and 25,500 barrels of commodity lost; $130,650 property damage and one nonemployee injury; $325,055 property damage and nine nonemployee injuries; and $100,000 property damage, two carrier employee deaths, and three carrier employee injuries.

Pipeline spills were the second largest source of oil pollution in coastal waters.[60] In 1971 there were 1,436 leaks spilling a total of 897,685 gallons. An evaluation of the spill data showed that approximately 90% of the offshore spills and 97% of the oil spilled comes from pipelines leading to wells less than three miles offshore. Most of the pipeline spillage is the result of failure of old pipelines.

Pipeline accidents are caused by a number of factors including equipment rupturing lines, internal and external corrosion, structural defects (seams, welds, repairs), human operating errors, vandalism, and natural causes. According to the Department of Transportation (DOT), Office of Pipeline Safety Operations, equipment rupturing lines (28.6%) and external corrosion (22.4%) accounted for about half of the accidents during 1975.[59] These accidents caused an estimated $757,500 in property damage and a loss of 120,797 barrels of oil, or 38% of the total oil lost in pipeline accidents.

Approximately 43% of the 73 accidents caused by equipment rupturing were the result of bulldozer, grader, and ditching machine operation. Of these 73 accidents, 47% involved the following activities:

1. Pipeline and cable construction (12 accidents, 16.4%),

2. Moving earth for commercial firms or local government (11 accidents, 15.1%), and

3. Clearing or grading of private land (11 accidents, 15.1%).

The DOT statistics also showed that 78% (57 accidents) of the corrosion caused accidents were due to external corrosion. This would be expected to occur with old pipelines since newer ones generally have protective coatings and cathodic protection. Seventy-two percent were in equipment installed between 1920 and 1949. However, 75.5% involved lines with cathodic protection. External corrosion accidents accounted for approximately $115,800 in property damage but resulted in no death or injury. Two-thirds of external corrosion accidents involved crude oil in the pipeline while the remaining involved gasoline (15.8%), fuel oil (12.3%), and jet fuel, furnace oil, and transmix (5.3%).

4.2.5 Transportation (Truck and Railroad)

Any unintentional release of hazardous materials in transportation must be reported to DOT's Office of Hazardous Materials Operation (OHMO). For purposes of perspective, a summary of hazardous materials rail and highway incident reports involving death or injury for 1974 and 1975 are presented in Table 36.[61]

TABLE 36. RAIL AND HIGHWAY ACCIDENTS[a]

	1974			1975		
	No. of Reports	Deaths	Injuries	No. of Reports	Deaths	Injuries
Rail	68	10	593	74	0	95
Highway	170	18	276	193	27	489

[a] Reference 61

These figures are based upon immediate notifications which are required when the release of hazardous materials results in death, injury, estimated property damage exceeding $50,000, or spillage of radioactive materials or etiolgic agents.

According to the DOT, 10 accidents accounted for 22 of the fatalities and 239 injuries. Of these 10, one can be classified as transportation by tank truck for non-end use. This accident occurred at Eagle Pass, Texas, on April 29, 1975, and involved loss of control of a liquified petroleum gas (LPG) tank truck. Explosion followed causing 15 deaths and 45 injuries. This one accident caused 56% of the total highway fatalities, and 9.2% of the injuries for the year. Of the hazardous commodities most frequently involved in accidents reported for 1975, gasoline accounted for 12.8% and LPG for 1% of the estimated 8,088.

LPG consists primarily of propane maintained as a liquid at elevated pressures. LPG is usually transported via truck, rail car, or tanker. Several major accidents involving transport of LPG have occurred, including the Eagle Pass incident cited above.

One of the most severe types of accidents which can occur is the BLEVE (Boiling Liquid Expanding Vapor Explosions). This occurs when a leak of LPG is ignited. The resulting fire heats tanks which have not been damaged. As long as the flame is heating the bottom portion of tank containing the LPG, the relief valve at the top will release the pressure from the resulting vapor. If, however, the flame is heating the part of the tank where the vapor is, extreme temperatures will cause the tank to melt and tear. When this happens, the vapor escapes and explodes. The explosion can have sufficient force to hurl projectiles over half a mile, generate fireballs over 1,000 feet high, and cause blasts felt over 4 miles away. One of the worst instances occurred in Kingman, Arizona on July 5, 1973. Ten minutes after a fire started from an LPG lead, a BLEVE occurred. Half of the tank truck was hurled 1,200 feet. Twelve firemen were killed and 95 bystanders were injured.

API has summarized motor vehicle accidents in the petroleum industry for 1975. According to their classification, Marketing - Wholesale includes bulk distribution of petroleum products, including truck and transport deliveries and related administrative activities. The figures, however, include retail marketing operations such as transportation of batteries and tires to marketing outlets. According to API there were 8 deaths, and 3,356 injuries of which 1,799 were lost time accidents among employees of the industry.

Rail accident data are generally all inclusive and not limited to type of cargo. DOT statistics for rail accidents for 1971 through 1975 involving hazardous materials are shown in Table 37.[61]

An analysis of accident risks pertaining to hazardous materials shipments by rail, truck, and barge has been completed.[62] Although the analysis focused on damage to cargo in the nuclear industry, many of the results apply to shipment of non-nuclear cargo.

The analysis was based on 1969 data for accidents involving impact, fire, or both. Arbitrary categories of accident severity were established in order to determine a relationship between accident rates and severity for the different modes of transportation. Auto accidents and grade-crossing accidents were not considered. (Rail cargo is rarely affected by grade crossing accidents.)

The probabilities for rail, truck, and barge accidents are shown in Table 38.[62] The accidents are categorized by degree of severity in terms of velocity of vehicle impact and incidence and duration of fire. The totals are a summary of each accident-severity category. Fire duration was believed to be unlikely to exceed 1/2 hour in all cases other than those involving ruptured tank cars or flammable liquids. It was estimated that 1.5% of all rail accidents involved fires of which 85% last less than 1/2 hour and 1% longer than one hour.

In 1969, for a total of 61 billion rail car miles, there were 4,971 accidents, other than at grade crossings, involving death, injury, or property damage in excess of $750. The overall accident rate was 0.15 train accidents per million car-miles. For other than rail-crossing accidents this dropped to 0.08 per million car-miles. Each accident involved an average of 10 rail cars. Most of the reported accidents were derailments (70%) and collisions (21%). Accidents with the highest probability of producing significant damage to shipment containers were those involving derailments.

For trucks, 38,813 accidents were reported in 1969 involving death, injury, or property damage in excess of $250. The overall accident rate was 2.5 accidents per million vehicle-miles while for accidents involving hazardous materials the rate was 1.7 per million vehicle-miles. Package damage was severe in all types of truck accidents, but most severe in collisions with rigid, stationary objects and roll-overs. Fire generally occurred in 0.8% of truck-truck collisions, 0.3% of truck-auto collisions, 0.6% of truck-fixed-object collisions, 2% of truck-train collisions, and 1% of roll-over accidents. Major fire of more than 1/2 hour duration generally occurred in the case of the truck-truck accident where significant amount of fuel was available (e.g., a tank loaded with a fuel). Of all vehicle accidents, 50% involved truck-auto or bus collisions, while 14% involved collisions with fixed objects, 0.6% with trains, and 9.5% involved roll-overs.

TABLE 37. SUMMARY OF RAIL ACCIDENTS INVOLVING HAZARDOUS MATERIALS, 1971-1975[a]

YEAR	NUMBER OF ACCIDENTS	PERSONS KILLED	PERSONS INJURED	NUMBER OF EVACUATIONS	PERSONS EVACUATED
1971	80	1	57	16	3,005
1972	99	0	226	18	5,274
1973	123	2	384	32	29,647
1974	148	10	613	28	10,911
1975	186	0	20	19	4,755

[a] Reference 61

TABLE 38. ACCIDENT PROBABILITY[a]

SEVERITY CATEGORY	VEHICLE SPEED (mph)	FIRE DURATION (hr)	PROBABILITY PER VEHICLE MILE		
			Rail	Truck	Barge[b]
Minor	0-30	<1/2	$6\text{x}10^{-9}$	$6\text{x}10^{-9}$	-
	0-30	0	$4.7\text{x}10^{-7}$	$4\text{x}10^{-7}$	$1.6\text{x}10^{-6}$
	30-50	0	$2.6\text{x}10^{-7}$	$9\text{x}10^{-7}$	$1.4\text{x}10^{-7}$
Total			$7.3\text{x}10^{-7}$	$1.3\text{x}10^{-6}$	$1.7\text{x}10^{-6}$
Moderate	0-30	1/2-1	$9.3\text{x}10^{-10}$	$5\text{x}10^{-11}$	-
	30-50	<1/2	$3.3\text{x}10^{-9}$	$1\text{x}10^{-8}$	$8\text{x}10^{-9}$
	50-70	<1/2	$9.9\text{x}10^{-10}$	$5\text{x}10^{-9}$	$2\text{x}10^{-9}$
	50-70	0	$7.5\text{x}10^{-8}$	$3\text{x}10^{-7}$	$3.4\text{x}10^{-8}$
Total			$7.9\text{x}10^{-8}$	$3\text{x}10^{-7}$	$4.4\text{x}10^{-8}$
Severe	0-30	>1	$7.0\text{x}10^{-11}$	$5\text{x}10^{-12}$	-
	30-50	>1	$3.9\text{x}10^{-11}$	$1\text{x}10^{-11}$	$9.3\text{x}10^{-11}$
	30-50	1/2-1	$5.1\text{x}10^{-10}$	$1\text{x}10^{-10}$	$1.3\text{x}10^{-9}$
	50-70	1/2-1	$1.5\text{x}10^{-10}$	$6\text{x}10^{-12}$	$3.3\text{x}10^{-10}$
	70	<1/2	$1\text{x}10^{-11}$	$1\text{x}10^{-10}$	-
	70	0	$8\text{x}10^{-10}$	$8\text{x}10^{-9}$	-
Total			$1.5\text{x}10^{-9}$	$8\text{x}10^{-9}$	$1.6\text{x}10^{-9}$
Extra Severe	50-70	>1	$1.1\text{x}10^{-11}$	$6\text{x}10^{-13}$	$2.3\text{x}10^{-11}$
	70	1/2-1	$1.6\text{x}10^{-12}$	$2\text{x}10^{-13}$	-
Total			$1.3\text{x}10^{-11}$	$8\text{x}10^{-13}$	$2.3\text{x}10^{-11}$
Extreme	70	>1	$1.2\text{x}10^{-13}$	$2\text{x}10^{-14}$	-
Total			$1.2\text{x}10^{-13}$	$2\text{x}10^{-14}$	-

a. Reference 62.

b. Barge accident probabilities are based on the duration of the fire and actuarial data on cargo damage. The impact velocities of all barge accidents were considered to be less than 10 mph, but for the purpose of this table, minor cargo damage is assumed to be equivalent to land vehicle impact speeds of 0-30 mph; moderate cargo damage, 30-50 mph; and severe cargo damage, 50-70 mph.

Analysis of the data indicates that the probability of an accident occurring generally was similar for each mode of transportation. Therefore a single value for each accident-severity category can be used in general accident risk assessment. The probability that an accident with a particular severity will occur is:

Minor	Moderate	Severe	Extra-Severe	Extreme
1×10^{-6}	3×10^{-7}	8×10^{-9}	1×10^{-11}	1×10^{-13}

on a per vehicle-mile basis.

Accidents involving truck loading racks were not considered in the probability analysis. According to the Oil Insurance Association, losses from explosion and fire at loading racks are small considering the large volume of flammable petroleum liquids which are handled daily in this manner.[64] However, an accident at a loading rack may cause dollar losses greater than $100,000 and loss of life. A study indicated that static electrical ignition, human error, and equipment failure accounted for the largest portion of the overall loss total in leading rack accidents.[64] Other causes were electrical ignition, vehicle damage, and wind and lightning. Contributing factors were:

1. Fast loading rates (between 500 and 1,200 gpm) which generates static electricity,
2. Extensive use of product filters which are producers of static electricity,
3. Dryer, cleaner products (especially in the distillate range) which retain static charges for longer period of time,
4. Increased handling of more hazardous products,
5. Extensive use of aluminum tank trailers of larger capacity which can fail structurally within a minute when exposed to intensive ground fires,
6. Larger, more complicated loading racks,
7. Limited availability of land causing congestion and undue exposure to other facilities and tankage,
8. Key-stop (unattended) operations, which because of reduced supervision, reduces the possibility of controlling fires once started, and
9. Inexperienced staff because of high labor turnover.

4.2.6 Storage Tank Accidents

The storage of large quantities of crude oil or products at various points in the crude oil chain from production to retailing present a potential for a major accident. This type of accident involves fire and explosion and generally results in loss of property rather than life.

Tank fires generally are caused by overfilling, poor housekeeping and maintenance practices, and lightning. The severity of the resulting fire depends on tank spacing, common diking, piping within dikes, and availability of water and foam to fight fires.

According to the Oil Insurance Association (OIA) the potential for large dollar losses has increased due to the increase in crude oil prices and the resulting increase in the value of finished products.[5] In addition, there is a trend toward jumbo tanks, those larger than 300,000 barrel capacity. Tanks of from 300,000 to 1,000,000 barrels are being used for storing crude oil as well as intermediate and finished products, the latter with various ranges of flammability.

The risk of accident can present a serious loss exposure problem as illustrated by the following example involving a 500,000 barrel tank filled with crude:

Value of contents @ $10 per barrel	$ 5,000,000
Cost of rebuild after a fire @ $4 per barrel of capacity	$ 2,000,000
Total loss exposure	$ 7,000,000

Since the trend is to install the tanks at least in pairs and often in groups of four to ten or more, the potential loss exposure can be high.

4.2.7 Refinery Accidents

The refinery, which contains a number of process units which produce petroleum products (e.g., LPG, gasoline, jet fuel, diesel fuel, distillate fuel oil, residual fuel oil, etc.) is the source of many accidents. Major accidents involve fire and explosion wihch result in extensive property damage and may cause death and injury.

Many injuries and deaths are associated with refinery accidents. API data for the refining element indicates that in 1975 there were 5,915 injuries and illnesses associated with the job, of which 1,846 were lost time accidents (approximately 1/3), and 3 were fatalities. However, data from the National Petroleum Refiners Association indicates that there were 8,155 injuries, of which 2,623 were lost time accidents, and 11 were fatalities.[65]

Important secondary problems of the refinery accident involving fire and explosion are air pollution and oil spills. They create a potential problem to both the worker and the bystander in terms of health and property damages.

The air pollutants characteristic of an oil fire are carbon monoxide (CO), sulfur dioxide (SO_2), oxides of nitrogen (NO_x), hydrocarbons (HC), and particulates. While the cloud formed as a result of fire and explosion generally dissipates rapidly, prolonged exposure of these pollutants can cause at least temporary illness. An atmospheric inversion in the area of such an occurrence would prevent the normal dispersion of the pollutants, thus increasing the change of exposure.

Hydrorefining units, such as the hydrocracker and hydrotreater which use hydrogen, are widely used in petroleum processing. Statistics compiled by the OIA indicate that hydrorefining units have the greatest potential for accidents, in terms of frequency and severity, of any current refining process.[65]

Losses due to accidents for various processes from 1965-1969 are summarized in Table 39.

TABLE 39. ACCIDENT LOSS SUMMARY FOR VARIOUS PROCESSES, 1965-1969

Process	Loss Summary No. of Accidents	1965-1969 Total Amount of Losses	Approximate Average Loss
Catalytic Cracking	32	$3,308,000	$103,000
Catalytic Reforming	59	3,134,000	53,000
Hydrocracking	19	6,402,000	337,000
Crude/Vacuum Units	57	1,366,000	24,000

There are several factors to be considered with regard to figures in Table 39.

1. At the end of 1969 there were 5 1/2 times as many catalytic crackers as hydrocrackers. Therefore, hydrocrackers had a loss frequency rate more than 3 1/2 times that of catalytic crackers, with a severity rate more than triple.

2. Almost all catalytic crackers on stream at the end of 1969 had operated throughout the full five years but few hydrocrackers had been in service that long.

3. The loss frequency rate for hydrocrackers was 3 times that of catalytic reformers, while the severity rate was more than 6 times greater, there being [illegible] 1/2 times as many catalytic reformers on stream as hydrocrackers.

4. Until the time of this study, the catalytic reformer had been the most hazardous process in terms of frequency and size of losses.

Hydrocracker losses since 1970 averaged well over $1,000,000. Loss trends for hydrocrackers, in terms of frequency and severity from 1962-1971, are shown in Figure 7.*

The principal cause of hydrocracker accidents was failure of the heater tube in the hydrotreater section. A much less important cause was charge pump failure. Accidents due to other causes were negligible.

Alkylation units, which chemically combine two hydrocarbon molecules into a single molecule, have been considered by the Oil Insurance Association (OIA) to have had a relatively good accident record. However, accidents involving these units can cause significant property damage. Because volatile, heavier than air chemicals can be involved in the accidents, large areas can be affected by fire and explosion.

There are two types of alkylation units, the sulfuric acid (H_2SO_4) and hydrofluoric acid (HF). In 1970 there were approximately 70 of each type in the United States and Canada combined. The H_2SO_4 units had an average production capacity of approximately 7,500 barrels per stream day compared with 3,500 barrels per stream day for the HF units. Large units of both types are becoming increasingly common.

During the period from 1961 to 1972 there were 18 known alkylation unit accidents. Five were H_2SO_4 units and 13 HF units, or greater than a 2:1 loss of HF units. In addition, there have been no known H_2SO_4 unit losses since 1967, whereas HF unit losses began in 1965 and increased in frequency and severity ever since. HF unit accidents may be due to their age, or deficiencies in operating or maintenance procedures. Nearly 25% of the losses were caused by drain valves being left open and unattended.

The 18 unit accidents represent damage in excess of $6,800,000. Three of the units were covered by Business Interruption Insurance, which represented an additional $1,400,000. Four of the 18 accidents caused property damage in excess of $1 million. These 4 units were all less than average size.

A study was made of losses exceeding $10,000 occurring in gasoline plants, which may or may not be part of a complete refinery.[67] A determination was made of the equipment which initiated the accident and the dollar amount of the loss for each type (Table 40). Pumps accounted for 38% of the damage in dollars but only for 10% of the number of accidents.

Damage from individual accidents can exceed $1,000,000. For example, in one incident a fire in a lean oil pump area resulted in extensive damage to a refrigeration absorption gasoline plant. The fire was extinguished in one hour but it caused $2.3 million in damage and 6 months downtime.

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* Statistics for hydrorefining units covered the period from 1965 through 1969.[51] Data compiled after 1970 is not comparable to data for the prior period because only larger losses were reported due to higher deductibles. However, frequency and severity of hydrocracker accidents probably have continued to increase.

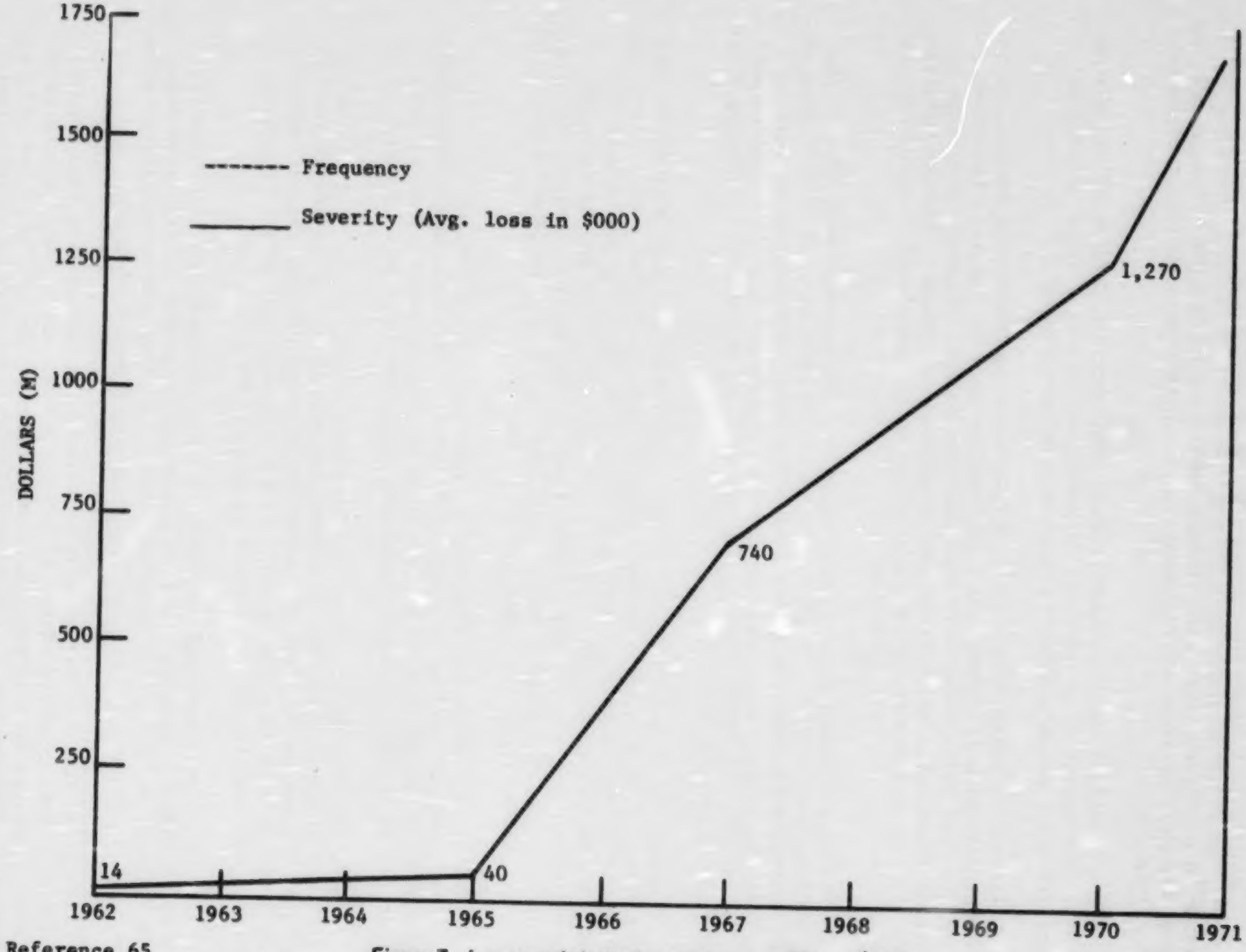

Figure 7. Loss trends in hydrocrackers – 1962 to 1971[a]

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[a] Reference 65

TABLE 40. LOSSES OVER $10,000 OCCURRING IN GASOLINE PLANTS DURING THE YEARS FROM 1959 THROUGH 1971[a]

INITIATING EQUIPMENT	NUMBER OF ACCIDENTS	LOSS (DOLLARS)
Heaters	32	1,001,700
Pumps	13	6,271,700
Gas Compressors	23	3,387,700
Tanks	6	1,721,900
Piping Failures (Includes Gasket Failures)	11	2,718,500
Boiler Fire Box Explosions	7	150,000
Service Buildings	12	262,000
Other	10	401,100
Wind	16	390,000
Hail	4	252,900
TOTAL	134	16,558,300

[a] Reference 67

Special consideration was given to the fired heaters as a major source of accidental fire by OIA.[68] These heaters find application in refineries, petrochemical plants, and other oil and gas facilities. Insurance company figures show that more than 200 such fires cost the industry more than $9 million in property damage and production losses between 1965 and 1969.

These heaters are found in a number of process units, including those previously discussed. Table 41 shows these losses in terms of each type of unit.

TABLE 41. REFINERY PROCESS UNIT LOSSES ORIGINATING IN FIRED HEATERS[a]

PROCESS CATEGORY	% OF PROCESS UNIT LOSSES ATTRIBUTABLE TO EACH CATEGORY	% OF LOSSES IN EACH CATEGORY ORIGINATING IN FIRED HEATERS
Hydrocracking	7.6	43.7
Catalytic	15.2	18.7
Catalytic Reforming (Including Hydrotreating)	27.9	44.1
Polymerization Isomerization Alkylation	5.2	9.0
Solvent Refining	0.5	100
Crude, Vacuum Distillation	27.0	30.0
Thermal Processes (Coking, Visbreaking)	16.6	22.9
TOTAL	100.0	

[a] Reference 68

SECTION 5.0

NATURAL GAS

5.1 RESOURCE SYSTEM OVERVIEW

Natural gas is composed primarily of methane (CH_4) with small amounts of ethane (C_2H_6), butane (C_4H_{10}), propane (C_3H_8), and heavier hydrocarbons. Natural gas may also include water, gaseous sulfur containing compounds, nitrogen, and carbon dioxide. It may occur three ways: non-associated (very little conjunctive crude oil), dissolved in crude oil, or associated (as in the case of a gas-cap where the gas accumulates in the area overlying the oil pool).

In 1950, the total annual consumption of natural gas in the United States totalled 6,150 trillion BTUs. By 1970, consumption has increased to 22,029 trillion BTUs. This amounted to annual increase of 6.5%. Other energy demands grew only by 3.5% during the same time period. In 1950 natural gas supplied 18% of the total energy demand. In 1970, this had grown to 32%.

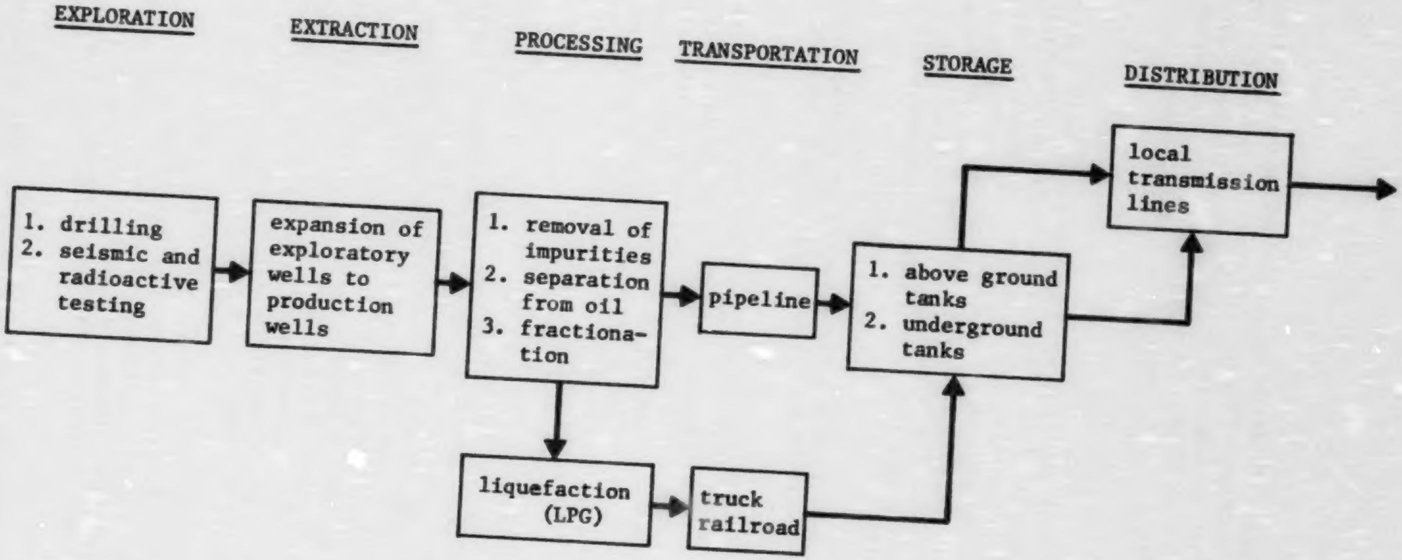
In 1974 the Federal Power Commission estimated the domestic supply of the lower 48 states and Alaska to be from 1,000 to 2,955 tcf. The proven reserves at the close of 1973 totalled 250.0 tcf for the entire United States. Of this, 218.3 tcf were attributed to the lower 48 states with approximately 36.1 tcf offshore and 182.2 tcf onshore. Approximately 88% of the natural gas reserves in the lower 48 states are located in Texas, Oklahoma, Louisiana, New Mexico, and Kansas. At the current rate of production, the reserves would be exhausted in 11.1 years.

5.1.1 Exploration

The elements in the natural gas energy cycle are shown in Figure 8. Exploration and production of natural gas is similar to exploration and extraction of crude oil (Sections 4.1.1 and 4.1.2). These functions are briefly reviewed below.

The initial step in locating new oil and gas reserves involves identifying promising geological formations. This is followed by an in-depth study of each possible site and finally exploratory drilling. The "bright-spot" technique using seismic and radioactive methods has proven useful in the detection of non-associated and associated gas reservoirs.

Exploratory drilling is required to determine whether gas and oil exist in larg e enough quantities to be profitable. Drilling of offshore formations presents more problems than onshore. Drilling equipment is mounted on a platform. These platforms are barges, drill ships, semi-submersibles, or jackups. Barges are used for shallow water drilling. Drill ships are used



EXPLORATION
EXTRACTION
PROCESSING
TRANSPORTATION
STORAGE
DISTRIBUTION
1. drilling
2. seismic and radioactive testing
expansion of exploratory wells to production wells
1. removal of impurities
2. separation from oil
3. fractionation
pipeline
1. above ground tanks
2. underground tanks
local transmission lines
liquefaction (LPG)
truck
railroad

Figure 8. Natural gas energy system.

in depths of 500 to 3,000 feet. A jackup is self-elevating and has buoyant hulls so that the platform drilling rig can be floated to the site. When it reaches the site, the legs are jacked down to the ocean floor and the platform elevated to the appropriate height. A semisubmersible is similar to a floating rig and is supported by displacement hulls or caissons.

5.1.2 Production

After discovery of natural gas, the well is tested to determine the size of the reservoir and the possible flow. Additional wells are drilled, carefully placed so as to control the flow and drain the reservoir as completely as possible. Completed development wells contain casing and tubing to carry oil and gas to the surface. In seismically active areas and offshore sites, a safety valve is installed near the bottom of the production tubing. This valve is activated to shut off flows when downhole pressures become uncontrolled.

The oil and gas is forced to the surface either by natural pressure or by artificial means. Artificial means include pumping and injection of another fluid.

In order to develop an offshore field a fixed drilling platform is constructed. From this, between twenty and forty production wells are drilled. After all the production wells are drilled, the drilling equipment is removed and production equipment is installed. Subsea production systems are becoming increasingly common. These systems involve placing well-heads on the ocean floor rather than on platforms. Oil and gas is then pumped to a nearby fixed platform or shore facility.

5.1.3 Processing

The processing of natural gas involves its separation from associated oil, water, sand, sulfur, carbon dioxide, and other impurities. The actual processing method chosen depends upon the composition, location of source, and end use. Usually, the fluids are first treated to remove water and sand by physical separation, use of dehydrants, and skimming. After removal of impurities, the fluids are sent through a sequence of separators to separate the oil from the gas. Hydrogen sulfide (H_2S) is removed by extraction with ethanolamine. Because of the corrosive and toxic nature of hydrogen sulfide, special care is taken with gases containing H_2S. The gas is then compressed, fed through a gathering system, and into a high pressure transmission line.

If the gas is rich in methane, it may be processed at natural gas plants rather than in the field. Besides separating the oil from the gas, these plants separate the liquid into fractions. The plants produce liquified petroleum gas (LPG), gasolines, ethane, and heavier liquid hydrocarbons. Much of the gas produced is used to supply the processing and field energy requirements.

If oil and gas are produced jointly, separation must occur in offshore facilities as well as onshore. If the gas contains water, it is dehydrated by contact with glycol, pressurized, metered, and pumped to shore by pipeline.

If there is no pipeline, or it is economically unattractive to produce the gas, the gas is pressurized and reinjected into the reservoir. A typical production facility and associated safety devices are shown in Figure 9.

5.1.4 Transportation

Domestic gas is transported by pipeline. Pipeline systems have diameters from 12 to 42 inches and are usually constructed of steel pipe. They are usually buried from 2-4 feet below the surface. The gas is compressed to 600-1,000 psig and the resulting pressure drives the gas through the pipeline. Valves are installed every 10 to 30 miles along the pipeline to enable isolation of a section if a large drop in pressure occurs. Pipelines are coated to protect them from chemical corrosion. In urban areas care must be taken to prevent corrosion from electrical currents. Stray electrical charges may cause loss of metallic ions, resulting in a weakening of the pipeline. One method to guard against this is cathodic protection in which a direct current is applied to the pipe.

Construction of offshore pipelines presents special problems. In the past, pipelines were laid directly on the ocean bottom. Now if the water depth is less than 200 feet, the pipelines are buried to minimize potential of damage from natural forces and marine equipment. Pipes are lowered by a barge into trenches dug by high pressure water jets. Because of access difficulty once laid, pipes are very carefully inspected.

5.1.5 Storage

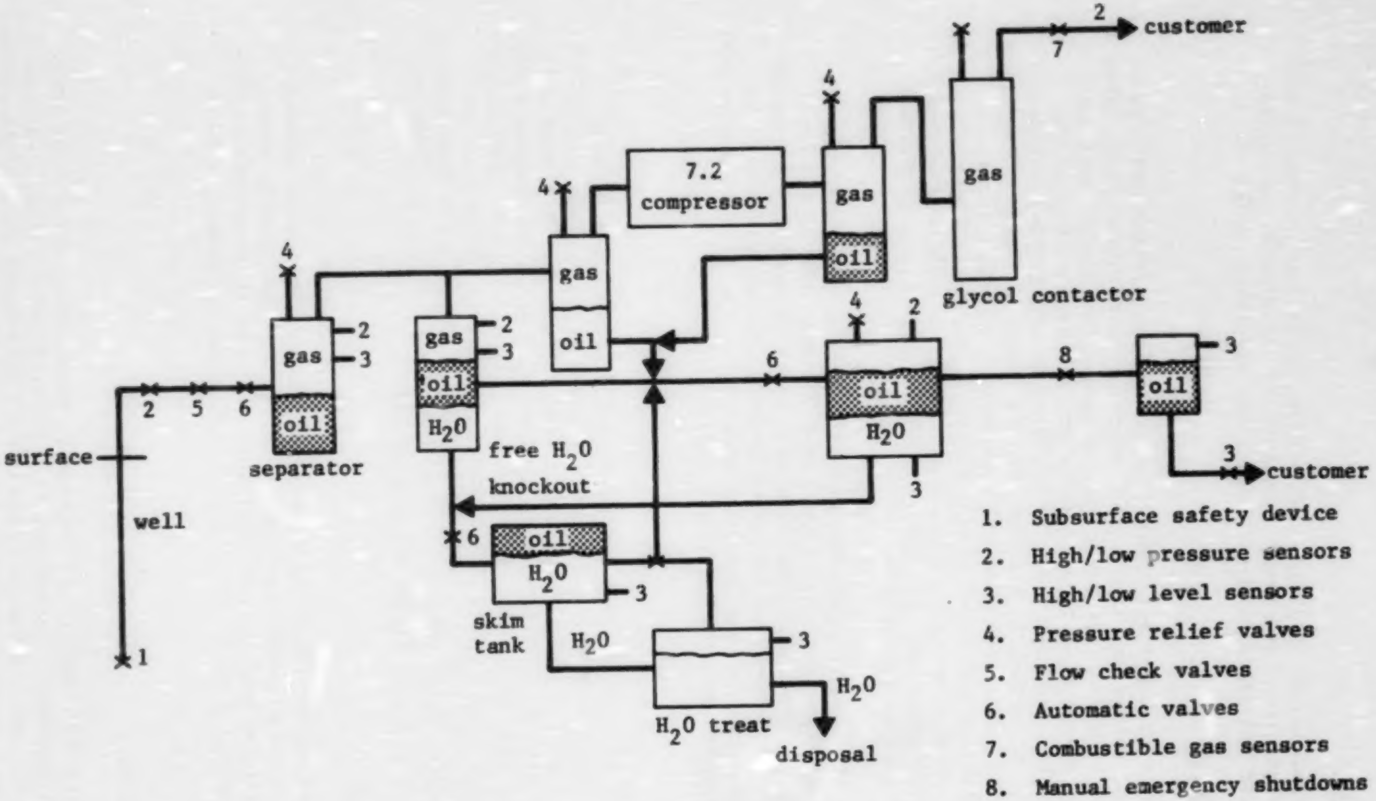
Natural gas is often stored at its destination for periods of peak demand. In 1974, there were approximately 367 underground storage fields with a total capacity of 6,364 billion cubic feet. Often gas is stored underground in depleted oil or gas reservoirs, aquifers, caverns, and sealed mines. These areas must be gas tight, have a large capacity, and support high production and intake rates. Because of small capacity, storage of natural gas above ground in tanks is used only on a local basis to meet daily peak demands. During times of extreme demand, peak-shaving plants are operated. These introduce a mixture of air and LPG to the gas stream.

5.1.6 Distribution

The local distribution of gas to commercial residential users involves a system of mains, valves, regulators, and meters. The gas usually enters the local distribution system through city gate stations at pressures of 100-150 psig. Mains operating at 25-35 psig feed individual customer lines at 0.25-0.35 psig.

5.2 ACCIDENT OVERVIEW

Table 1 presents a summary of the accidents associated with the exploration, extraction, processing, transportation, and storage of natural gas and their related severity and frequency. Blowouts of well-heads during the drilling of exploratory and production wells, release of sulfur compounds during


customer
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H2O
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1
H2O
H2O treat
disposal

1. Subsurface safety device
2. High/low pressure sensors
3. High/low level sensors
4. Pressure relief valves
5. Flow check valves
6. Automatic valves
7. Combustible gas sensors
8. Manual emergency shutdowns

Figure 9. Typical production facility with safety equipment.[a]

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[a] Reference 42

processing, and failures of pipelines from corrosion or outside forces comprise the bulk of the accidents occurring from this energy source. Sudden, uncontrolled release of gas may result in fires and explosions causing injury to nearby persons and damage to equipment. Accidents affecting the general public may arise from pipeline failures because these transect residential and commercial areas.

Table 42 presents injuries and man-days lost per billion BTUs in the natural gas industry.[15] Pipeline distribution accounts for the greatest number of injuries and man-days lost at 0.0138 injuries/10^{12} BTU and 0.324 man-days lost/10^{12} BTU. Onshore extraction accounts for the largest number of deaths at $8.1 \times 10^{-5}/10^{12}$ BTU.

Table 43 shows the occupational injuries and illnesses for 1975 for natural gas operations subject to OSHA record keeping requirements.[34] Drilling had the highest frequency at 48.93 disabling injuries per million man hours worked. This is an order of magnitude higher than for exploration and production, processing, and pipeline transportation.

Table 44 shows the annual impact of an uncontrolled gas-fired electricity generating system associated with a 1,000-megawatt power plant with a load factor of 0.75.[1] Extraction is responsible for the greatest number of deaths and injuries. The total number of annual deaths was 0.20 with 0.16 attributed to the extraction of natural gas. The total number of injuries was 18.3 with 16.0 attributed to extraction. Total number of lost work-days was 1,986 with 1,629 attributed to extraction.

The results of the American Petroleum Institute Review of Fatal Injuries in the Petroleum Industry for 1975 are shown in Table 45.[35] A total of 12 fatalities occurred in 1975. Seven were attributed to exploration and production. (There is, however, no distinction made between oil and gas.) No fatalities occurred in gas processing, 2 occurred in drilling, and 3 occurred in pipeline transportation of gas.

Table 46 presents data on employee disabling injury frequency and severity by type of gas between the years 1970 and 1974.[69] The frequency for all natural gas in 1974 was 9.08 where frequency is defined as number of disabling injuries per million man-hours worked for each injury resulting in a minimum on one day's loss of time. The severity rate was 357 where severity is defined as number of days lost due to disabling injuries per million man-hours worked.

The severity and frequency rates for gas utilities are compared to other industries in Table 47.[69] The utilities had the lowest severity rate but the second highest frequency rate.

5.2.1 Exploration Accidents

Exploration accidents occasionally result from improper use of explosives or radioactive pellets. One to three such incidents are reported each year.

TABLE 42. ACCIDENT RATES FOR EXTRACTING, GATHERING, PROCESSING, TRANSMITTING, DISTRIBUTING, AND STORING NATURAL GAS[a]

	ACCIDENT RATE PER 10^{12} BTU EQUIVALENTS		
	FATALITIES	INJURIES	MAN-DAYS LOST
Extraction			
Offshore	6.9×10^{-6}	0.003	0.01
Onshore	8.1×10^{-5}	0.004	0.13
Gathering			
Pipeline	3.1×10^{-6}	0.001	0.025
Processing			
Natural Gas Liquid	4.1×10^{-5}	0.004	0.097
Hydrogen Sulfide	2.1×10^{-6}	0.002	0.005
Transmission and Distribution			
Pipeline	4.0×10^{-5}	0.0138	0.324
LPG Trucks	U	U	U
Storage			
Underground	U[b]	U	U
Gas Holders	U	U	U

[a] Reference 15

[b] Unknown

TABLE 43. REPORTS OF OCCUPATIONAL INJURIES AND ILLNESSES FOR THE YEAR 1975 COVERING OPERATIONS SUBJECT TO OSHA RECORDKEEPING REQUIREMENTS ONLY[a]

FUNCTION	NUMBER OF EMPLOYEES	RECORDABLE CASES			FATALITIES	TOTAL LOST WORKDAY CASES	NON-FATAL CASES WITHOUT LOST WORKDAYS	INCIDENCE RATE[f]			FREQUENCY RATE
		INJURIES	ILLNESSES	TOTAL				TOTAL CASES	LOST WORKDAY CASES	NON-FATAL W/O LOST WORKDAYS	
Exploration & Production[b]	54,598	2,466	36	2502	9	763	1730	4.4	1.35	3.07	6.57
Drilling[c]	1,918	515	0	515	2	196	317	25.45	9.69	15.67	48.93
Gas Processing[d]	5,927	299	1	300	2	69	229	4.87	1.12	3.72	5.61
Pipeline-Gas[e]	16,736	921	28	949	3	168	778	5.75	1.02	4.71	4.97
Total	79,179	4,201	65	4266	16	1196	3054	5.27	1.47	3.77	7.23

[a] Reference 34.
[b] Same as Table 4.3 note b).
[c] Same as Table 4.3 note c).
[d] Processing of gas to produce liquid hydrocarbons (e.g., ethane, LPG, and natural gasoline).
[e] Gas gathering and truck/line operations of natural gas transmission lines, excluding retail distribution.
[f] Per 100 employees.

TABLE 44. ANNUAL ACCIDENT IMPACT OF AN UNCONTROLLED GAS-FIRED ELECTRICITY SYSTEM ASSOCIATED WITH A 1,000-MEGAWATT POWERPLANT WITH A LOAD FACTOR OF 0.75[a]

	EXTRACTION	PROCESSING	TRANSPORT	CONVERSION	TRANSMISSION	TOTAL
Deaths	0.16	0.01	0.02	0.009	N.A.	0.20
Injuries	16.0	0.05	1.2	1.09	N.A.	18.3
Workdays Lost	1,629	92	145	120.4	N.A.	1,986

[a] Reference 1

TABLE 45. FATALITIES BY FUNCTION AND CAUSE FOR THE NATURAL GAS INDUSTRY YEARS 1975 AND 1974[a]

	CASES REPORTED		FIRE AND EXPLOSION		STRUCK BY EQUIPMENT		MOTOR VEHICLE		AIRCRAFT		OTHER CAUSES	
	1975	1974	1975	1974	1975	1974	1975	1974	1975	1974	1975	1974
Exploration & Production	7	19	0	5	1	0	1	3	1	6	4	5
Gas Processing	0	0	0	0	0	0	0	0	0	0	0	0
Drilling	2	1	0	0	1	1	0	0	0	0	1	0
Pipeline	3	3	0	0	0	1	2	1	0	0	1	1
Total	12	13	0	5	2	2	3	4	1	6	6	6

Total (1974 + 1975) = 35 fatalities

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a. Reference 35.

TABLE 46. EMPLOYEE DISABLING INJURY FREQUENCY AND SEVERITY RATES, BY TYPE OF GAS, 1950-1974[a,b]

YEAR	REPORTING NUMBER	ALL REPORTING COMPANIES AVERAGE EMPLOYEES	GAS UTILITIES RATE FREQUENCY	GAS UTILITIES RATE SEVERITY	TOTAL NATURAL GAS RATE FREQUENCY	TOTAL NATURAL GAS RATE SEVERITY	NATURAL GAS DISTRIBUTION AND INTEGRATED COMPANIES RATE FREQUENCY	NATURAL GAS DISTRIBUTION AND INTEGRATED COMPANIES RATE SEVERITY	NATURAL GAS TRANSMISSION COMPANIES RATE FREQUENCY	NATURAL GAS TRANSMISSION COMPANIES RATE SEVERITY	MANUFACTURED AND MIXED GAS RATE FREQUENCY	MANUFACTURED AND MIXED GAS RATE SEVERITY
1970	0	200,493	6.34	548	6.34	554	6.66	522	5.02	686	6.09	236
1971	1	210,589	7.15	473	7.17	478	7.48	444	5.70	634	6.29	208
1972	2	205,371	8.38	535	8.44	542	8.98	495	5.88	762	5.42	183
1973	3	207,423	8.18	547	8.18	547	8.77	373	5.67	1,287	b	b
1974	4	208,283	9.08	357	9.08	357	9.75	362	6.12	333	b	b

[a] Reference 69.

[b] Frequency rate is number of disabling injuries per million man-hours worked for each injury resulting in a minimum of one day's loss of time. Severity rate is number of days lost due to disabling injuries, per million man-hours worked.

TABLE 47. EMPLOYEE ACCIDENT FREQUENCY AND SEVERITY RATES OF SELECTED INDUSTRIES, 1974[a]

	FREQUENCY[b]	SEVERITY[b]
Gas utilities	10.20	614
Electric utilities	7.41	942
Mining, surface[c]	9.75	1,365
Mining, underground coal[c]	35.44	5,154
Petroleum[d]	6.73	690

[a] Reference 69

[b] Frequency rate is number of disabling injuries per million man-hours worked for each injury resulting in a minimum of one day's loss of time. Severity rate is number of days lost due to disabling injuries per million man-hours worked.

[c] 1972 data

[d] 1973 data

The most disastrous type of accident that can occur during exploratory drilling is a blowout. A blowout is the result of a sudden release of pressure resulting in unconstrained flow. Oil and/or gas surges up the hole causing a loss of control over the well. If the impact pressure is sufficiently great, physical damage to the drilling rig may result. If ignition occurs, fires will result causing damage to equipment and death and injury to persons in the area.

Safeguards have been developed to forestall such blowouts. Drilling mud, a viscous mixture of clay and water is circulated around the drilling bit to counteract a sudden flow. Drill holes are encased at the top with steel pipe set in cement to minimize the possibility of a blowout around the outside of the drill.

Various devices are used during drilling operations and in producing wells to reduce or eliminate a blowout. The blowout preventer (BOP) is located in a stack arrangement outside the drill pipe between the surface casing and the rotary drilling table. It is generally used to control flows during drilling operations. On fixed offshore platforms they are located on the platform above the last string of casing, while on a semi-submersible or drill ship they may be on the sea floor, also above the last string of casing. The bag and the ram are the two types of blowout preventers. They are operated by fluid pressure to close the well opening in order to regain control of pressures in the hole by means of drilling muds.

Subsurface safety valves are located inside the tubing of producing wells and are either pressure activated or hydraulically controlled. Their purpose is to control pressure in the well. A blowout preventer may be used with a producing well if it is being drilled deeper and if there is the possibility of losing control during workover and the downhole safety devices have been removed.

5.2.2 Production Accidents

Blowouts are possible during the drilling of production wells as well as exploratory wells. However, the potential is greatly lessened because the surrounding geology is much better known and successful exploratory wells have been drilled. Subsurface safety valves are designed to trigger an immediate shut down of the drill hole in case of sudden change in pressure. Currently, this is an area of special interest and much research. Several downhole valves have failed. In 1970, 10 of 42 valves in Shell's Bay Marchand Fire failed. In 1971, 4 of 10 valves failed at an Amoco facility leading to a fire. Because of these events USGS has modified its regulations to include as standard requirements remotely activated valves which are hydraulically operated and controlled from the surface.

Loss of well control may occur during servicing of rigs. Service personnel may not work for the company operating the rig, and consequently may be unfamiliar with operating procedures. A new technique has been developed for use in servicing procedures which allow insertion of downhole tools in a separate parallel circuit while the well is sealed off. This greatly reduces the risk of an unscheduled release of gas. Other safety equipment installed on production rigs and platforms include pressure, level, and combustible gas sensors, pressure relief valves, and fire detection and fighting equipment.

5.2.3 Processing Accidents

Processing accidents are those occurring during the separation of oil and gas and the removal of impurities. Special care must be taken in treating sour gases, i.e., those containing H_2S.

Hydrogen sulfide is odorous and corrosive whether as a free gas or dissolved in petroleum. Concentrations of approximately 0.005% cause sub-acute poisoning when breathed for long periods of time. Inhalations of concentrations of 0.06-0.08% have resulted in death in experiments with animals. Combusion of hydrogen sulfide will generate sulfur dioxide (SO_2) and sulfur trioxide (SO_3). These compounds cause respiratory irritation in humans when present in concentrations about 5 ppm. Sensitive individuals will notice 1 to 2 ppm and experience bronchial spasms at 5-10 ppm.

Table 42 shows that gas processing for hydrogen sulfide removal was related to 2.0×10^{-6} deaths per 10^{12}BTUs and 0.002 injuries per 10^{12} BTUs. Table 43 shows that gas processing was responsible for 921 injuries and 3 fatalities in 1975.

5.2.4 Transportation Accidents

Almost all pipeline accidents can be attributed to corrosion damage by outside forces, construction defects, or material failure. Corrosion may be internal or external. External corrosion may result from the action of sea water, ground water, soils, and sediments. Internal corrosion is caused by hydrogen sulfide, water, or acidic conditions.

External corrosion is lessened by use of coatings, cathodic protection, and use of materials which resist corrosion, such as plastic, aluminum, and stainless steel. Internal corrosion can be lessened by interior coatings, injecting corrosion inhibitors, and chemicals. Chemicals include oxygen scavengers to reduce dissolved oxygen concentrations, dehydrants, and bases.

Several examples serve to illustrate the accidents which may occur. In Bainbridge, Georgia, on August 26, 1975, a two-inch steel pipeline suffered damage from an outside force. It had an open end and inadvertant opening of a valve permitted gas to escape. The gas migrated under the pavement and into the post office. An explosion and fire resulted killing one person in the post office and injuring two others.[70]

In Hugo, North Carolina, on September 29, 1975, three fatalities occurred from a fire and explosion resulting from the escape of natural gas into an air conditioning control room. The accident was traced to the weight of a sewer line causing a split in polyethylene service line carrying 45 psig 12 feet from the building.

The National Transportation Safety Board investigated a pipeline failure near Monroe, Louisiana, on March 2, 1974. A 30-inch gas transmission pipeline failed inside a 34-inch casing pipe. Gas burst from a ruptured weld in the 30-inch line. It blasted a trench 100 feet long, 30 feet wide, and 25 feet deep. The trench cut through a state highway. The gas ignited and the fire burned 10 acres of forest and sterilized the soil for 700 feet along the pipeline. No deaths or injuries occurred.

The Eighth Annual Report of Pipeline Safety summarized gas pipeline accidents during 1975 by distribution and transmission and gathering categories (Table 48).[70] There were 9 non-employee fatalities; 8 associated with distribution and 1 associated with transmission. There were 5 employee fatalities; all were associated with transmission and gathering. There were 200 non-employee injuries; 191 associated with distribution and 9 with transmission and gathering. There were 37 employee injuries; 29 associated with distribution and 8 associated with transmission. There were 1,373 failures. This amounts to approximately 0.01 deaths per failure and 0.11 injuries per failure. Damage by outside forces accounted for 71% of the failures, corrosion for 10%, construction defects for 12%, and other causes for 7%. Table 49 shows the number of failures and resulting injuries and fatalities for 1970 through 1975.[70]

The American Gas Association has prepared a report on the analysis of incidents reported to the Office of Pipeline Safety between 1970 and 1973. In 1970, all companies were required to file a report with the Department of Transportation of all reportable accidents. A reportable accident is defined as:

1. Causing death or personal injury requiring hospitalization,
2. Requiring removal of a segment of pipeline from service,
3. Resulting in a gas ignition,
4. Causing damage in excess of $5,000,
5. Significant in the judgment of the operator, or
6. Requiring immediate repair and other emergency action to protect the public.

Table 50 shows incidents by leaks, and leaks and ruptures by age.[6] There were 3327 total reportable accidents in the time period or one incident/year/1213 miles of pipeline in use.

Table 51 shows that between 1970 and 1973 there were 2274 (68.3%) accidents resulted from outside forces.[6] Corrosion caused 479 (14.4%) and 352 (10.6%) were caused by construction or natural defects. A plot of numbers of incidents versus year of occurrence illustrates the importance of outside forces as a cause of pipeline accidents. (Figure 10.)[6]

The risks to persons and property were evaluated in terms of fatalities, injuries, cost to industry, and damage to operator's property. The number of

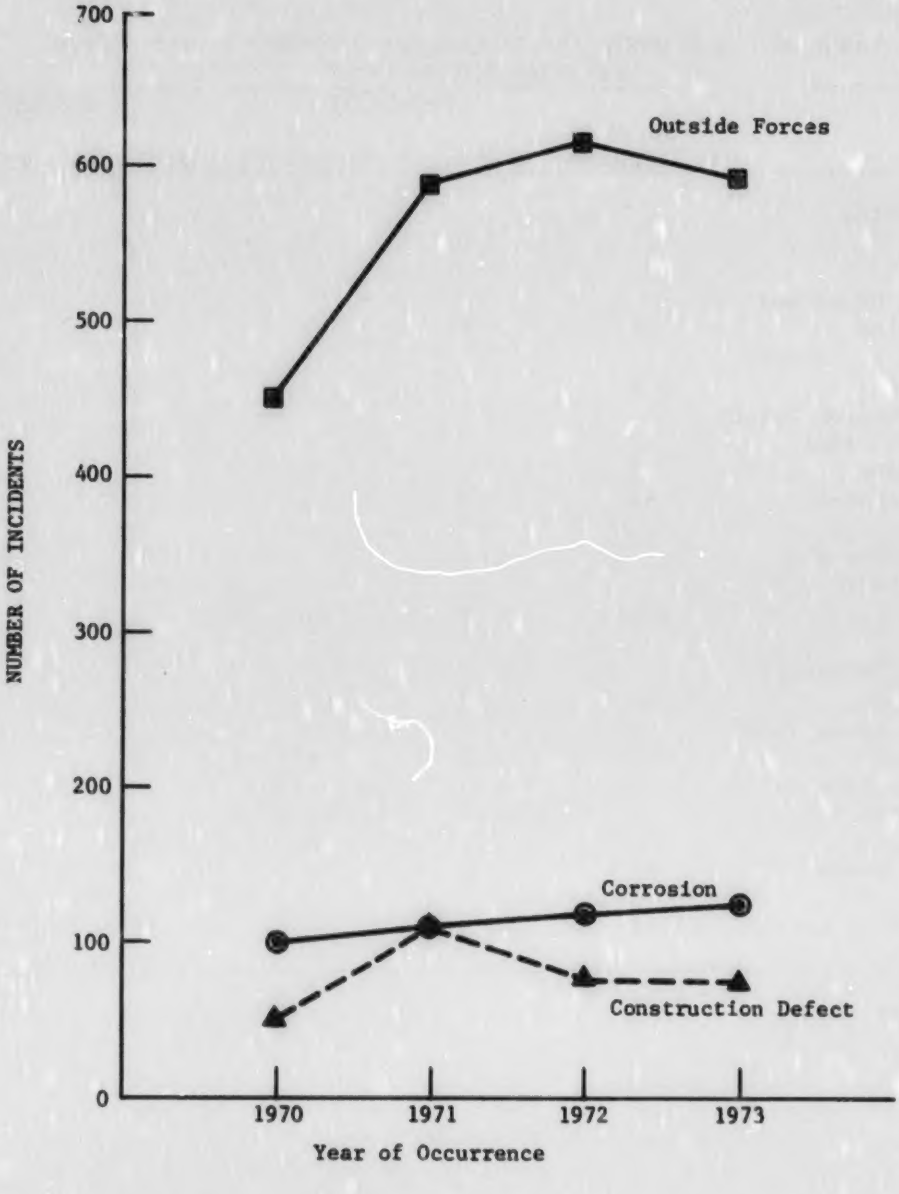

Figure 10. Number of incidents and cause versus year of occurrence.[a]

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[a] Reference 6.

TABLE 48. ACCIDENTS AND CASUALTIES REPORTED BY GAS SYSTEM OPERATORS DURING 1975[a]

	TOTAL NO. OF FAILURES	FATALITIES		INJURIES	
		EMPLOYEES	NON EMPLOYEES	EMPLOYEES	NON EMPLOYEES
Distribution					
Total	979	0	8	29	191
Subtotal by cause:					
Corrosion	94	0	1	6	23
Damage by outside forces	744	0	5	7	119
Construction defect or material failure	78	0	0	1	25
Other causes	63	0	2	15	24
Transmission and gathering:					
Total	394	5	1	8	9
Subtotal by cause:					
Corrosion	44	3	1	2	4
Damage by outside forces	237	0	0	0	5
Construction defect or material failure	88	1	0	5	0
Other causes	25	1	0	1	0
Gas industry totals	1,373	5	9	37	200

[a] Reference 70

TABLE 49. SUMMARY OF GAS PIPELINE ACCIDENTS AND CASUALTIES REPORTED DURING YEARS 1970-1975[a]

	DISTRIBUTION					TRANSMISSION AND GATHERING				
		FATALITIES		INJURIES			FATALITIES		INJURIES	
CALENDAR YEAR	NO. OF FAILURES	EMPLOYEES	NON EMPLOYEES	EMPLOYEES	NON EMPLOYEES	NO. OF FAILURES	EMPLOYEES	NON EMPLOYEES	EMPLOYEES	NON EMPLOYEES
1970	676	1	20	32	170	343	1	0	8	8
1971	875	6	36	36	329	410	2	1	14	10
1972	884	2	26	32	262	409	3	3	23	13
1973	893	1	32	48	285	471	1	1	3	16
1974[b]	1,017	1	19	31	283	460	1	3	7	13
1975[b]	979	0	8	29	191	394	5	1	8	9

[a] Reference 70.

[b] Includes data from telephonic reports to the Office of Pipeline Safety Operations (OPSO). Data from telephonic reports were not included in accident casualty data for years 1970-1973.

TABLE 50. NUMBER OF INCIDENTS BY YEAR OF PIPE INSTALLATION[a]

AGE OF PIPELINE (YEARS)

RUPTURES

YEAR	N.A.[b]	76-105	66-75	56-65	46-55	36-45	26-35	16-25	6-15	LESS THAN 5	TOTAL
1970	57	1	5	7	6	10	28	45	73	14	246
1971	47	5	4	10	27	15	33	72	93	44	350
1972	54	2	4	11	23	28	31	64	89	78	384
1973	81	2	3	8	30	30	47	59	105	104	469
Total	239	10	16	36	86	83	139	240	360	240	1449
LEAKS AND RUPTURES											
1970	135	6	14	23	44	45	72	136	164	37	786
1971	127	21	13	26	61	61	96	179	197	96	877
1972	119	9	13	18	65	72	82	181	191	132	882
1973	147	10	9	16	66	53	100	151	175	165	892
Total	528	46	49	83	236	231	350	647	727	430	3327

a. Reference 6.

b. NA = Information on age not available.

TABLE 51. NUMBER OF INCIDENTS BY CAUSE IDENTIFIER[a]

YEAR OF OCCURRENCE	NA[b]	CORROSION	OUTSIDE FORCES	CONSTRUCTION DEFECT AND MATERIAL FAILURE
1970	59	104	465	48
1971	58	121	576	122
1972	43	121	630	90
1973	65	133	603	92
Totals	225	479	2,274	352

[a] Reference 6

[b] NA = Information on age not available.

fatalities and injuries is summarized in Table 52.[6] In 1973 there were 893 incidents of pipeline failure. There was 1 employee and 32 non-employee fatalities or one fatality per 27 accidents. There were 48 employees and 285 non-employee injuries or one injury per 2.7 accidents.

Ninety-six percent of the corrosion related incidents were externally caused. In 83% the corrosion was galvanic (associated with an electrical current). Table 53 shows that twice as many accidents were caused by pitting as other sources.[6] Coated and cathodically protected pipe had a much lower failure rate than pipe which was bare or was only wrapped, coated, or cathodically protected.

Sixty percent of the accidents resulting from outside influences were caused by equipment operated by an outside party (Table 54).[6] Other causes of damage were earth movement (14.1%), vehicle (7.3%), weather (4.8%), pipeline company operated equipment (3.2%), willful damage (1.4%), and other (8.8%).

A tabulation of service interruptions and causes appear in Table 55.[71] For 1974 the total number of interruptions was 71. Outside forces were again responsible for the majority of failures; 42 of the 71 (59%) were attributed to action of the elements and earth-moving equipment.

The American Petroleum Institute report on occupational injuries and illnesses for 1975 indicates that out of 949 incidents, 3 fatalities, 921 injuries, and 28 illnesses resulted (Table 43).

5.2.5 Storage Accidents

Long term storage of gas involves risks of leaks and ruptures. Accidental release of gas may result in fires and explosions causing damage to equipment and injury and loss of life to persons in the vicinity. Harm to the public is also possible because these storage facilities are often in densely populated areas. Above-ground tanks are especially susceptible to damage from outside forces. For this reason, much work has been done in the development of underground storage facilities. Most often, these are naturally formed cavities.

Depleted oil and gas reservoirs are the most developed forms of underground storage available in the United States today. Their ability to hold a fluid has already been proven. If the gas is to be stored at pressures greater than those present at discovery, several safety precautions are taken. This is because additional pressure may cause fracturing of surrounding rock formations and the subsequent escape of gas. Observation wells are drilled and completed above the storage horizon and around the flanks in the same horizon as the reservoir so that escaping gas can be detected quickly. Corrosion protection measures must also be taken to prevent leakage of gas. If the storage facility is located in a populated area, equipment should be placed underground in concrete vaults as protection against vehicles and vandals.

Aquifers may also be used for underground storage. Besides the precautions enumerated above, it is necessary to insure that gas will not migrate

TABLE 52. CONSEQUENCES OF INCIDENTS[a]

	YEAR				
	1970	1971	1972	1973	TOTAL
Number of Employee Fatalities	1	6	2	1	10
Number of Employee Injuries	32	37	32	48	149
Number of Non-Employee Fatalities	20	36	26	32	114
Number of Non-Employee Injuries	170	330	262	285	1047
Number Ignited	275	493	501	505	1774
Number of Explosions Occurred	91	164	170	161	586
Number of Secondary Explosions or Fires	55	123	115	98	391
Estimated Damage in $1000	197	297	574	520	1588
Underground Facility Contributed	70	64	100	86	320

[a]Reference 6

TABLE 53. NUMBER OF CORROSION INCIDENTS[a] BY CORROSION DESCRIPTION

YEAR	NA	PITTING	GENERAL
1970	5	64	35
1971	1	72	48
1972	3	82	36
1973	3	93	37
TOTALS	12	311	156

[a] Reference 6

TABLE 54. NUMBER OF OUTSIDE FORCE INCIDENTS BY PRIMARY CAUSE[a]

YEAR	N.A.[b]	EQUIPMENT OPERATED BY/FOR OPERATOR	EQUIPMENT OPERATED BY OUTSIDE PARTY	EARTH MOVEMENT	WEATHER	WILLFUL DAMAGE	VEHICLE	OTHER
1970	-	9	330	56	8	9	35	18
1971	1	18	345	87	30	6	35	54
1972	-	25	349	99	37	10	51	59
1973	1	20	348	78	35	7	46	68
Total	2	72	1372	320	110	32	167	199

a. Reference 6.

b. NA = Information on age not available.

TABLE 55. STATISTICS OF INTERSTATE NATURAL GAS PIPELINE COMPANIES-1974[a]

SERVICE INTERRUPTIONS OCCURRING ON THE PIPELINE SYSTEM

CAUSE	NUMBER OF INTERRUPTIONS	DURATION (HRS.)
Action of elements--flood, hurricane, etc.	24	338
Corrosion		
External	0	0
Internal	0	0
Coupling failures	0	0
External explosion	7	15
Fatigue failures	0	0
Line-pipe failure during test	1	30
Pipeline damaged by plow or other earth moving equipment	18	181
Weld failures		
Field weld	2	6
Longitudinal	0	0
Miscellaneous	16	78
Unknown	3	792
TOTAL	71	1441

[a] Reference 71

from the storage area and contaminate potable water aquifers. To prevent this, observation wells are closely monitored. Pilot gas injection is started slowly, preferably using an inert gas to trace movement of the fluid.

Salt caverns are suitable areas for storing gas because they are formed by a leaching process which creates a gas tight container. Hazards arise from extreme pressure changes causing structural failures which may allow gas to escape from the cavern. To be sure this does not occur, pressure changes must be monitored constantly. If escape does occur, highly saline leachate could contaminate potable water supplies and fresh surface waters.[72]

SECTION 6.0

LNG

6.1 RESOURCE SYSTEM OVERVIEW

Liquified natural gas, LNG, is composed of liquified methane (95%) with small impurities of propane (1%), butane (3%), nitrogen (5%), other hydrocarbons (0.2$). Methane becomes a liquid at -260°F. In the liquid phase it occupies a volume only 1/600 of its gas phase volume. It is this great volume reduction that makes liquefaction desirable because it enables large quantities of gas to be transported across the seas. Some physical properties of LNG appear in Table 56.[73] LNG is classified as a cryogenic (from the Greek kyros meaning icy cold and genes, born of) material and it is its cryogenic properties which render it hazardous.[74] If contact occurs, the low temperature will cause damage to human tissues. If LNG suddenly vaporizes, it may ignite and burn, causing injury and loss of life and damage to property in the vicinity.

LNG was first used during the early 1940's in peak shaving plants. A disastrous accident in Cleveland in 1944 at a storage facility costing 130 lives and $10,000,000 in damage greatly retarded growth of the industry. There are now 23 liquefaction plants, 49 operational peak shaving plants, and 40 satellite storage facilities in the United States. The total storage capacity is 12 million barrels.[75]

Currently, storage facilities without a liquefaction plant are supplied by tank trucks carrying 10,000 to 11,000 gal (238-262 bbl) LNG. Transport by barge and rail is being considered by DISTRIGAS via 30,000 barrel barges from Staten Island to Brooklyn and Queens, N.Y. DISTRIGAS operates the only currently functioning LNG terminal. In the first nine months of 1976, twelve tankers delivered 1,200,000 bbl of LNG. Four more tankers are expected before the end of the year.

There now exist major LNG shipping routes between Algeria and U.S., Alaska and Japan, Borneo and Japan, Algeria and England, France, Libya and Spain and Italy. There are proposed routes from the Persian Gulf to India and Japan, Nigeria to the U.S., Europe and Brazil, Alaska to United States West Coast, Carribean via Venezuela to the United States, Ecuador to the United States West Coast, New Guinea to the United States West Coast and Japan, and Indonesia to the United States West Coast.

Three base load plants are planned for Alaska (one is now operational) and 13 import receiving terminals are proposed with three operational, 3 under construction, and 7 in planning and approval stages. The planned LNG terminals and their status are listed in Table 57.[75]

TABLE 56 - PHYSICAL PROPERTIES OF LNG AND ITS CONSTITUENTS[a]

	Methane CH_4	Ethane C_2H_6	Propane C_3H_8	Iso-Butane C_4H_{10}	Normal Butane C_4H_{10}
Composition of typical peak shaving LNG (mole %)	95.9	2.5	0.9	0.12	0.15
Composition of typical Algerial LNG (mole %)	87.4	8.4	2.4	0.5	0.7
Molecular weight	16.04	30.07	44.09	58.12	58.12
Melting points °C (1 atm)	-182.5	-188.3	-187.7	-159.6	-138.3
Boiling points °C (1 atm)	-161.5	- 88.6	- 42.2	- 11.7	- 0.6
Liquid specific gravity (at boiling point)	0.425	0.550	0.580	0.562 (normal	0.581 temperature)
Gas specific gravity (air=1)	0.554	1.038	1.522	2.006	2.006
Critical temperature °C	- 82.1	32.4	96.8	135.0	152.0
Critical temperature (1 atm)	45.8	48.3	42.0	36.0	37.5
Evaporation latent heat (Kcal/Kg)	121.9	116.0	101.7	87.5	92.1
Total calorific value	9,520	16,820	24,320	31,530	32,010
Natural ignition temperature °C	537		466		405
Heated gas ignition temperature °C	1,325		990		990
Combustion range in air %	5.0-15.0		2.2-9.5		1.9-8.5

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[a] Reference 73

TABLE 57

PROJECTED LNG IMPORT/RECEIVING TERMINALS IN THE U.S.[a, b, c]

Company and Plant Site	Storage Capacity		Liquefaction-Vaporization Capacity MMcf/day)	Year of Operation
	MMcf	MBbl		
DISTRIGAS CORP. Everett, MA	3250	974 (1x375+1x600)	135	1971
PUBLIC SERVICE ELEC & GAS OF NEW JERSEY Staten Is., N.Y.	6000	1800 (2x900)	360	1973-1975
COLUMBIA LNG CORP & CONSOLIDATED SYSTEM LNG CO, Cove Pt., MD	5000	1500 (4x375)	1000 200	1976-Base Load Plant
ALGONQUIN LNG INC. (EASCOGAS LNG, INC.) Providence, RI	6000	1800 (3x600)	300 375	1973-1st tank 2 add'l. pending
NATURAL GAS PIPELINE CO. OF AMERICA (Peoples Gas) Ingleside, TX	5500	1600 (2x800)	400	1977-planned
TRUNKLINE LNG CO. Lake Charles, LA.	6000	1800 (3x600)	---	1977-planned
NORTHWEST NATURAL GAS CO., Newport, OR	1200	348	100	1976-under construction
WESTERN LNG CO.[d] Terminal Is., Los Angeles Harbor, CA	7700	2200 (4x550)	400 (4000)	48 mos. after approval
SOUTHERN ENERGY CO. Elba Island, GA	4000	1200 (3x400)	540	1976-under construction
TRANSCO TERMINAL CO. Racoon Is., N.J.	6000	1800 (3x600)	---	1977-planned
WESTERN LNG CO.[d] Oxnard, CA.	4000	1100 (2x550)	520 (4000)	48 mos. after approval

[a] Reference 75.

[b] Includes three liquefaction plants and storage for export in Alaska.

[c] Offshore terminal locations not included.

[d] Only one site (if any) will be chosen for an LNG terminal.

(continued)

(concluded)

TABLE 57

Company and Plant Site	Storage Capacity MMcf	MBbl	Liquefaction-Vaporization Capacity MMcf/day)	Year of Operation
WESTERN LNG CO.[d] Pt. Conception, CA	7700	2200 (4x550)	3200	48 mos. after approval
PHILLIPS-MARATHON[b] Kenai, AK	2300	675 (3x225)	90	1969
EL PASO ALASKA Pt. Gravina, AK	7700	2200 (4x550)	3375	1981-planned
PACIFIC ALASKA LNG[b] CO., Cook Inlet, AK	3000	1100 (2x550)	400	1979-planned

A study on projected LNG tanker fleet growth evaluated three possible growth rates for LNG imports.[76] The three cases were:

Case	Annual Volume Imported (Trillions of Cubic Feet) 1975	1980	1985	1990
1	0.2	2.2	3.5	5.0
2	0.2	1.3	2.2	3.5
3	0.2	1.2	1.3	1.3

The most likely growth pattern is between Cases 2 and 3. The projected sizes of LNG tanker fleets were:

Case	1975	1980	1985	1990
2	3	29	46	84
3	3	27	29	29

The projected source and quantity of LNG arriving in the United States for the years 1975, 1980, 1985 and 1990 are shown in Table 58. Half of the tankers were expected to be under the American flag.

By 1980 LNG trade may account for 6% of the world's natural gas consumption. According to one projection, the U. S., Europe and Japan will be importing 20 bcf/day of natural gas as LNG.[75]

An LNG system includes a natural gas source, transportation from source to liquefaction plant, liquefaction plant, storage and loading facilities at the export site, transportation by tanker, unloading and storage facilities at the import site, a regasification plant, and transmission to a major pipeline. Figure 11 is a diagram of an LNG resource system.

6.1.1 Exploration - See Natural Gas, Section 5.1.1.

6.1.2 Production - See Natural Gas, Section 5.1.2.

6.1.3 Processing - See Natural Gas, Section 5.1.3.

6.1.4 Transportation to Liquefaction Plant - See Natural Gas, Section 5.1.4.

6.1.5 Liquefaction

The two principal methods used for liquefaction are the cascade cycle and the expander cycle. The cascade cycle uses a series of refrigerants to sequentially lower the temperature. The refrigerants used are usually liquid propane, ethane, and methane. Propane is used first to decrease the temperature from 86°F to -44°F. The second stage uses ethane to decrease the temperature from

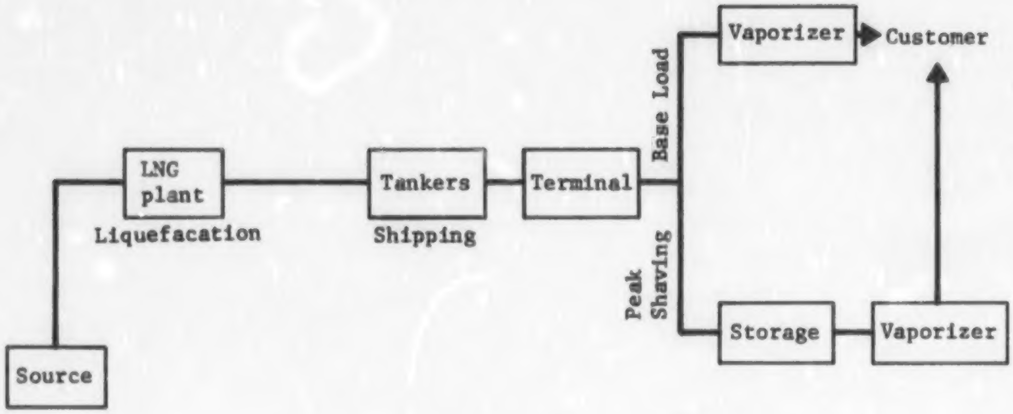
Vaporizer
Customer
Base Load
LNG plant
Liquefacation
Tankers
Shipping
Terminal
Peak Shaving
Storage
Vaporizer
Source

Figure 11. LNG operations.[a]

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[a] Reference 375

TABLE 58 - PROJECTED LNG IMPORTS[a]

Year	Export Country	Volume Tri. cubic ft/yr.	Number of Tankers
Case 2			
1975	Algeria	0.2	3
1980	Algeria	1.0	25
	Alaska	0.2	2
	Trinidad	0.1	2
	Total	1.3	29
1985	Algeria	1.2	28
	Alaska	0.2	2
	Trinidad	0.1	2
	Nigeria	0.4	10
	Venezuela	0.3	4
	Total	2.2	46
1990	Algeria	1.2	28
	Alaska	0.2	2
	Trinidad	0.1	2
	Nigeria	0.4	10
	Venezuela	0.3	4
	Australia	0.2	7
	Indonesia	0.4	14
	U.S.S.R.	0.7	17
	Total	3.5	84
Case 3			
1975	Algeria	0.2	3
1980	Algeria	1.0	25
	Alaska	0.2	2
	Total	1.2	27
1985	Algeria	1.0	25
	Alaska	0.2	2
	Trinidad	0.1	2
	Total	1.3	29
1990	Same as 1985.		

[a] Reference 76.

-35°F to -157°F. The final stage uses methane to accomplish the last reduction from -148°F to -258°F. A simplified diagram of the cascade system appears in Figure 12.

The expander cycle uses self-refrigeration. Compressed gas is expanded through an engine to extract work. At the same time the temperature of the gas is lowered. The amount of heat loss of the gas is controlled by the amount of the gas and expander inlet and outlet pressures. This method of liquefaction is used when large quantities of gas must be depressurized when going from transmission systems to distribution mains. Energy which would be lost can be used for liquefaction by reducing the gas pressure through a turbine. Unlike the cascade system, this method does not require the use of multiple refrigerants. Figure 13 is a simplified diagram of the expander cycle.

After liquefaction, additional purification must occur to remove any compounds which solidify at low temperatures. Examples of these substances are water, carbon dioxide (CO_2), hydrogen sulfide (H_2S), lubricating oils, odorants, and dust. If these solids are not removed, clogging of transmission units may occur.[74]

6.1.6 Storage

Between the time of liquefaction and tanker loading the LNG is stored in double walled metal tanks above ground. Tanks are of two types.

The first type has capacities up to 65,000 gallons and operates at pressures between 50 and 250 psig. These tanks consist of an inner liner of cryogenic material and an outer metal shell usually made of carbon steel. A list of cryogenic materials and their temperature limitations is contained in Table 59. Between the shell and the wall is an evacuated space filled with perlite.

A second type has a capacity of up to 1,200,000 gallons. In this case the LNG is stored at atmospheric pressures. The space between the inner and outer wall is filled with insulation in a dry inert atmosphere instead of a vacuum. A variation of this type contains a suspended deck which eliminates the need for a roof made of cryogenic material. The capacity of these tanks is up to 24,000,000 gallons.

6.1.7 LNG Tankers

Tankers for transporting LNG are of three types: free-standing, spherical, and membrane. These tanks differ in shape and insulating material. In all types, the LNG is contained in tanks in the ship's hold which are independent of the hull. In 1973, the largest tanker in operation was 75,000 cu. m.; however, several are being produced with a capacity of 125,000 cu. m.

6.1.8 Receiving and Regasification

To unload, LNG tankers connect to liquid unloading arms and the LNG is moved from the ships to cryogenic stainless steel or aluminum storage tanks.

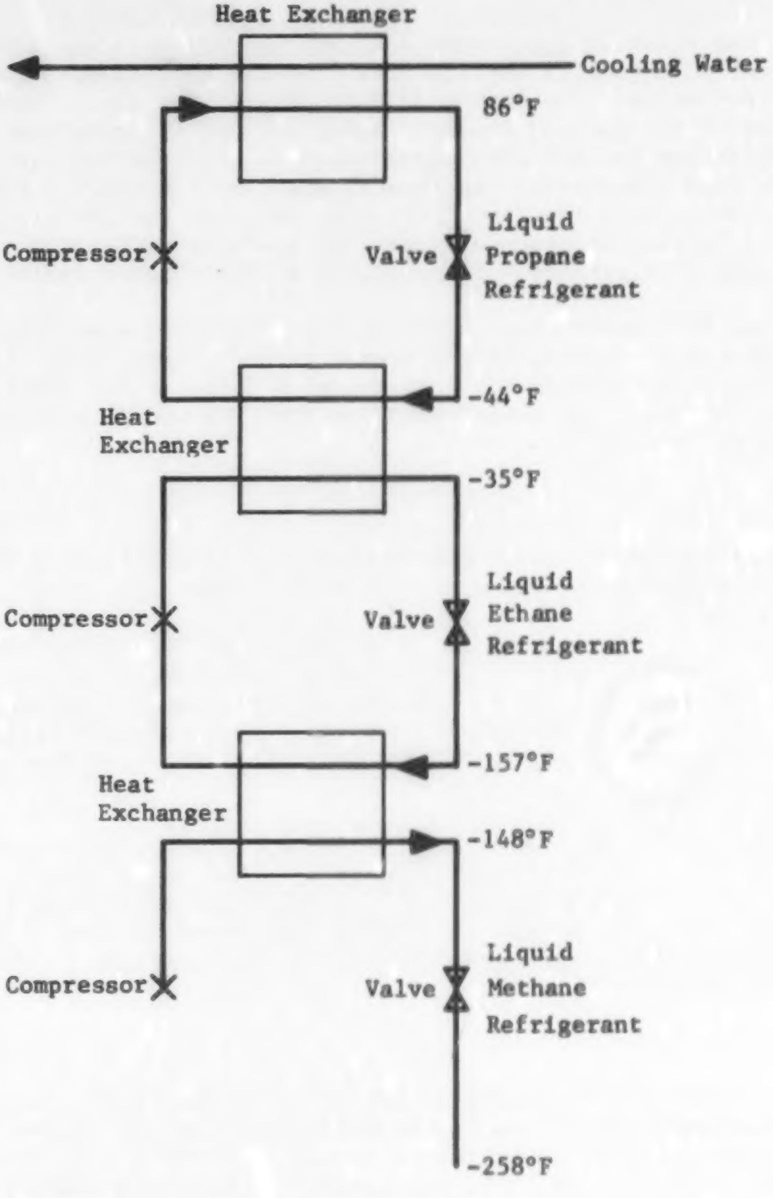
Heat Exchanger
Cooling Water
86°F
Compressor
Valve
Liquid
Propane
Refrigerant
-44°F
Heat
Exchanger
-35°F
Compressor
Valve
Liquid
Ethane
Refrigerant
-157°F
Heat
Exchanger
-148°F
Compressor
Valve
Liquid
Methane
Refrigerant
-258°F

Figure 12. Simplified diagram of cascade cycle for liquefaction of natural gas.[a]

[a] Reference 74

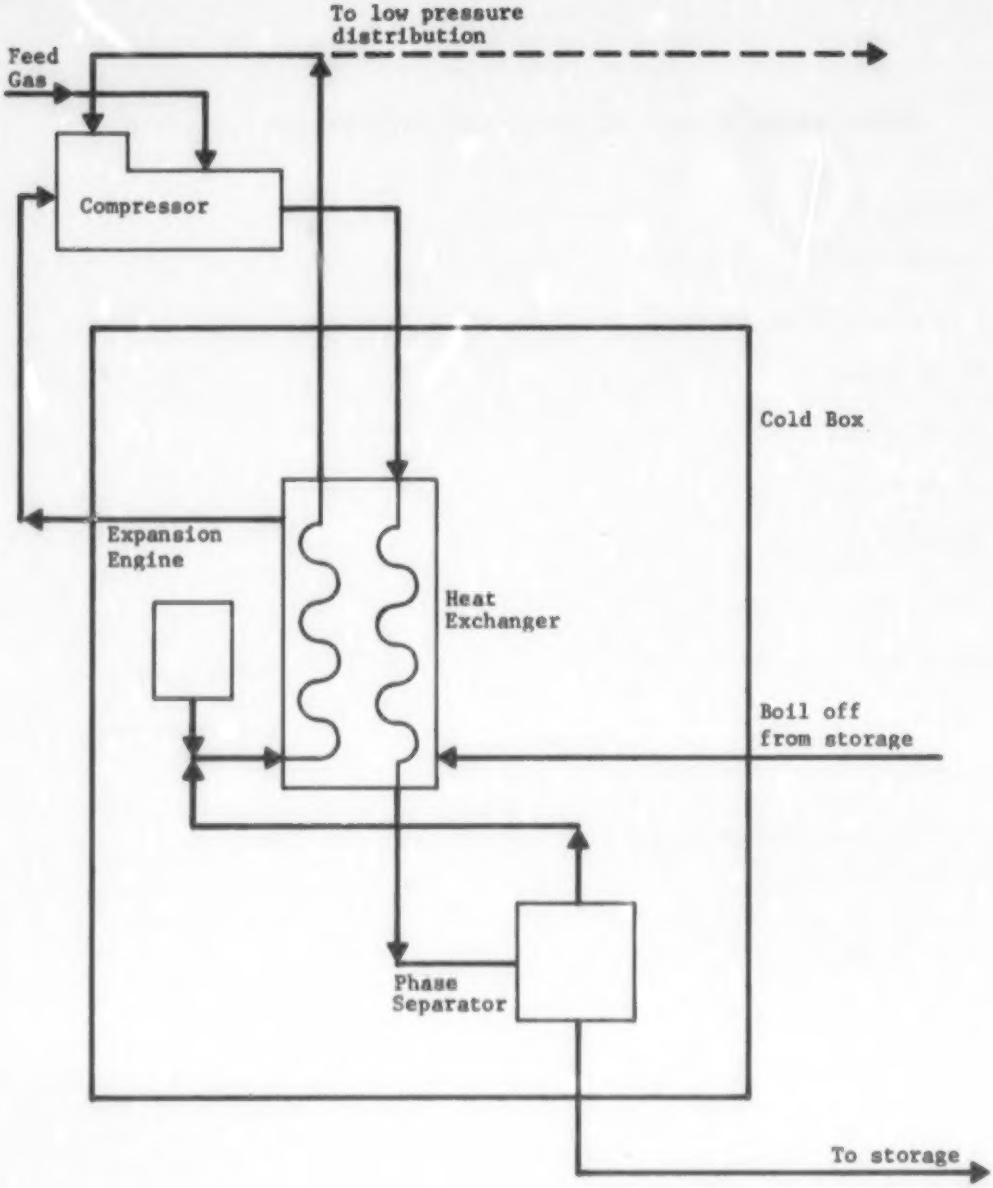
To low pressure distribution
Feed Gas
Compressor
Cold Box
Expansion Engine
Heat Exchanger
Boil off from storage
Phase Separator
To storage

Figure 13. Liquefaction by expander cycle.[a]

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[a] Reference 74

TABLE 59

CRYOGENIC MATERIALS AND ASSOCIATED TEMPERATURE LIMITATIONS[a]

Material	°F
Carbon steel	-22
Aluminum killed steel	-58
2% Ni steel	-76
3% Ni steel	-148
9% Ni steel	-328
Invar[R]	Durable well below LNG temperatures (-259°F)
18/8 stainless steel	
Austenitic steels	
Copper	
Aluminum	
Copper and aluminum alloys	

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[a] Reference 74

The LNG is regasified by passing it through heat exchangers at pressures of approximately 1200 psig. The LNG is then directly introduced into the pipeline.

6.1.9 Storage - See Natural Gas Section.

6.1.10 Distribution - See Natural Gas Section.

6.2 ACCIDENT OVERVIEW

Although the technology for reducing gaseous methane to the liquid phase has been known for several decades, the industry has experienced very slow growth. This is in part due to a catastrophic accident in 1944 in Cleveland, Ohio. A storage tank ruptured, and the ensuing explosions and fire killed 130 persons and caused $10,000,000 in damage. Recently, however, there has been increased interest on the part of the gas industry concerning importation of LNG.

Table 1 presents a listing of potential accidents associated with LNG and an estimate of frequency and severity. This table is based solely on an evaluation of likely accidents considering the technology involved. Those accidents which are considered to have the greatest potential for harm are groundings, failure of a storage tank, and a collision at sea involving an LNG tanker in which the contents of one or two tanks is released. Minor accidents include release of refrigerants and solids blocking the pipeline during or after liquefaction, onboard malfunctions of tankers, leaks in the system transferring LNG from tanker to onshore storage, and accidents during maintenance.

An LNG spill may occur on land in the case of a storage facility, on water in the case of a tanker spill, or underwater in the case of a tanker sinking. The consequences of each of these events are different.

If LNG is spilled on the ground, it begins to boil violently and vaporize. If the spill continues, a pool forms, freezes the ground underneath, and the boiling rate becomes constant. Several studies have been done concerning the consequences of an LNG spill on water.[77,78] If LNG spills on water, it is usually unconfined. It will spread rapidly and continue to boil at a high rate. If it is confined, an ice layer forms underneath. As this layer thickens the rate of heat transfer is reduced and the boiling rate is reduced.

If LNG spills, it will either ignite immediately or form a low-lying vapor cloud. This cloud is denser than air up to -40°F and will hover above the ground or water. The rate of generation of the vapor is proportional to the pool area. The vapor cloud will be cigar or pancake shaped. It will begin to rise when warmed sufficiently and its density drops to that of air. It will either eventually dissipate or be driven by the wind as a plume.

Distances a plume can travel before it falls below the lower flammable limit (LFL) are determined by meteorological conditions. Estimates range from 1 to 50 miles. Until the LFL is reached, ignition may occur at any time and involve flashbacks to the original pool. For LNG to ignite, it must form a

5 to 15% mixture with air and an energy source (frictional heating, electrical sparking, static electricity) must be present. The resulting fire will produce a radiant heat intensity greater than ignition of an equal amount of gasoline, but will be shorter lived.[8]

If LNG is released underwater because of a tanker accident, it is believed that the vapor will be greatly dissipated due to the heating of the water. The resulting flammable portion of the cloud rising from the water will be much smaller than from an equal size surface spill.[8]

Much speculation exists as to the likelihood of an LNG spill igniting immediately as opposed to formation and drifting of a vapor cloud some distance from the site of the spill. A 90% probability of immediate ignition is used in most of the literature reviewed on risk analysis modelling. However, this figure is arbitrary, and other values have been used.[8]

Another consequence of an LNG spill is the superheating of LNG in contact with water resulting in low energy, non-chemical explosions.[79,80] This phenomenon has been observed during experiments (tests by U. S. Bureau of Mines Safety Research Center at Pittsburgh during 1969; Continental Oil Company 1965; Shell Pipeline Company, in Houston, 1965; Esso Research in New Jersey; and Tokyo Gas Company, 1969) and during transport of LNG (second voyage of the Pioneer Methane in 1959 when 4900 gallons of LNG were pumped overboard in a period of 7 minutes, and at a Wisconsin Natural Gas facility when LNG was drained from storage into a pond).[79] These explosions result from sudden vaporization accompanied by a rapid increase in volume. A study done by the NAS in 1972 concludes "The nature of the explosion can be shown to have a relatively low potential for causing physical damage since it is flameless and not supported by the energy of a chemical reaction, only the energy of the superheat."[79]

In spite of the potential for severe accidents there have been only four major incidents involving LNG facilities. The most catastrophic was the Cleveland accident of 1944. A large storage tank containing 38,000 barrels of LNG collapsed. The collapse was later attributed to brittle fracture of the tank wall caused by exposure to cryogenic temperatures. The alloy of which the tank was constructed contained only 2% nickel and was not resistent to brittle fractures at temperatures below -76°F. Also, no dike existed to contain the spill. The resulting catastrophe involved a spreading pool fire. As it burned, the pool flowed into the surrounding residential and industrial area. Vapor accumulated in closed buildings and sewers and later exploded, demolishing many structures. Fire also spread by thermal radiation from the flame near the collapsed tank igniting combustible materials at great distances. The flame reached a height of 2800 feet. In all, 130 people were killed, 300 injured, 80 houses and 10 industrial plants destroyed, with a total property damage of $10,000,000. The likelihood of an accident of this sort recurring has been greatly reduced by the development of materials better able to withstand cryogenic temperatures (alloys now contain 9% nickel which can withstand temperatures up to -328°F), and the containment of spills through diking.

Three other accidents involved storage facilities. In February 1973, Texas Eastern's LNG storage tank on Staten Island exploded and burned. Forty workers were trapped and died.[75] The accident occurred during maintenance of the tank lining. Investigators concluded that although the tank had been emptied of LNG for one year, gas vapors had been trapped inside. The flame from a welder's torch ignited them, and the insulation caught fire.[75]

At the Northwest Natural Gas Facilities in Oregon a tank exploded during construction before the LNG was introduced. Four workers died. Investigators attributed the accident to careless work practices and not to LNG.[75]

In 1972, natural gas leaked through an air line to the control room of an LNG plant in Montreal, Canada. A large fire followed, creating more damage than would have occurred in an area of lesser importance.[75]

LNG accidents may be classified as two types - those occurring during marine operations, and those occurring during onshore operations. Accidents associated with marine phase of operations may be classified as malfunctions aboard the tanker and impact with a second body.

1. Onboard - Onboard malfunctions may involve spills and fires. LNG tanks are designed so that a fire in one tank will not ignite another. Care is taken to place tanks as far as possible from potential ignition sources. Onboard spills may cause imbrittlement and fracture of metal surfaces. Insulated catchments are standard equipment and should contain spills so that the ship and crew are not seriously threatened. Since there are spaces within which LNG vapor may accumulate by accident, the threat of fire cannot be ruled out.

2. Impact with a second body - This group of accidents includes collisions, rammings, and groundings. In rammings (ship to object impact) and groundings (ship to harbor floor impact) the impact point frequently is in the bow. Since the LNG tanks are located aft of the bow, many authorities believe they will not be affected in these types of accidents. Collisions (ship to ship impact) in which the LNG vessel is struck in its side by another ship are considered to be more serious.

In a collision, probably only one tank will rupture. Rupture of two tanks will occur only if impact takes place at a bulkhead intersection between two tanks. Consequently, the largest possible amount of LNG to be released will be 75,000 m^3 or the contents of two tanks, assuming 37,500 m^3 per tank.

Several measures may be taken to reduce the possibility of collisions, rammings, and groundings. These include crew training, installation of onboard safety devices, close Coast Guard surveillance including escorts, and deployment of a zone around LNG vessels excluding all other ships, or halting of all other traffic while the LNG vessel enters and docks.[8]

Accidents associated with the onshore phase may be classified as malfunction of the transfer system, damage to storage tanks, malfunction of vaporization plants, and malfunction of liquefaction plants.

1. Malfunction of Transfer System - The transfer arms, the LNG piping to the storage tanks, and the trestle carrying the piping are sites of possible accidents. The risks associated with these operations have been reduced to

low levels by the installation of safety devices. The potential risk to the public has been judged to be small relative to those occurring due to tankers or land storage tanks.

2. Damage to Storage Tanks - Storage tanks may internally rupture due to inadequate design, "roll-over" turbulence, rupture or external causes. "Roll-over" is a phenomenon resulting from improper mixing of LNG from different sources and of different compositions. If the heavier liquid is loaded from the bottom or the lighter liquid from the top, the liquids remain stratified. If the bottom layer heats, the densities equilibrate and rapid mixing ensues. This could create heating, boiling, and overpressures sufficient to rupture the tank. Careful loading and mechanical mixing have prevented accidents resulting from "roll over."

If a spill does occur damage will be minimized if the tank is diked and located far within the facility boundaries. LNG terminal construction is regulated by strict building codes. Design of a dike is critical to minimizing potential damage. The dike should be capable of containing more than 100% of the tanks' contents and its location and dimensions selected to assure damage will not extend beyond a facility's boundaries. The dike should provide a small surface area for any spill and have an insulated floor to minimize heating of the spilled liquid and maintain a low rate of vaporization. This will permit the cloud to dissipate before it reaches its LFL. Some dikes are broad and shallow. Some extend only a few feet from the edge of the tank so they are effectively only an outer wall. The former promote higher evaporation rates but are less vulnerable to a rupture from the same cause as that for the tank.

Although codes are in operation, controversy exists as to the safety of current designs. At public hearings in Cumberland, Rhode Island, in 1973, concerning the construction of an LNG storage tank, Dr. James Fay of MIT testified on behalf of the citizens that the National Fire Protection Code 59 for dike construction did not fully consider the formation of a [illegible]ing flammable cloud, and that existing requirements concerning distances between storage tanks and public buildings are too small. Dr. Elizabeth Drew testified on behalf of the utility that existing codes were adequate and provide ample protection to the public. It was decided that the tank would be built at the original site.

Tanks should have double walls to provide good insulation. The inner wall must be of a cryogenic material. An additional safety factor is gained if the outer wall is also cryogenic. In this way, the LNG would be adequately contained to allow draining if a rupture to the inner lining occurred.

3. Malfunction of Vaporization Plant - It is estimated that only small leaks of LNG or gas can occur in the piping from LNG tanks and in the vaporization process. Valve corrosion may occur leading to leaks and icing, and possible pressure buildups in piping sections. Insulation failures will cause frost, icing, and possible leaks. Safety practices of leak detection, spill prevention and containment, and fire warning devices greatly reduce risks to the public.

Insulation failures and escaping liquid or gas present the possibility of cryogenic burns from contact with cold liquid, vapor, or surfaces. The severity of the burn depends upon length of exposure, temperature of the source, and the rate of heat transfer. If the skin has surface moisture it may freeze onto the cold object. Skin may adhere to the cold surface when affected area is removed.

Prolonged exposure may also result in hypothermia, a decrease in body temperature. Physical and mental capabilities are greatly reduced if body temperature is decreased. Death results if temperature drops below 80.5°F. Vapors may reduce oxygen content so that asphyxiation occurs. This may occur sufficiently slowly that victim realizes it too late to save himself.

Protective measures against these physiological effects involve wearing safety glasses or goggles, non-conductive fire-resistant hard hats, protective clothing, gloves, and shoes.

Unless vaporization takes place at a constant rate, temperature cycling and sudden drops in temperature will create thermal stresses and lead to material weakening and possible failure.

4. Malfunction of Liquefaction Plants - Liquefaction plants have problems similar to vaporization plants. Insulation failures, pipe leaks, valve corrosion with pressure build ups, and thermal stresses occurring during start-up all may occur. An additional problem is the possibility of blockage by solids. When methane is liquified, impurities such as water and carbon dioxide may become solids. If these solids are not removed, they may block pipelines resulting in back-up pressure and possible rupture.

6.3 RISK ANALYSIS

Risk assessment follows three basic methodologies. These are logic tree modeling, analytical and simulation models, and statistical models. Logic tree analysis begins by considering a certain initiating event and then traces out all the possible events and sequences of events which could possibly occur as a consequence of this initiating event. An intrinsic problem with this kind of approach is that not all possible accident event sequences are accounted for. A second problem is the lack of assurance that failures arising from human error or inadequate design have been accounted for. A third problem is getting good estimates of component failure probabilities.

Analytical and simulation approaches model the performance of a system in terms of appropriate performance parameters. The performance parameters such as ship velocities and structural characteristics are formulated for given "scenarios." Probability distributions for particular conditions in the scenarios which will produce an accident are then calculated. Simulation models develop risk assessments as ratios of frequencies of occurrence of particular end events and the frequencies of occurrence of the system's activities. Analytical and simulation models are often labeled as arbitrary because of the necessary simplifying assumptions.

Statistical modeling obviates the problems associated with logic tree analysis and analytical and simulation models. It develops risk parameters, probabilities and consequences of accidents based upon historical data. Because it is based upon actual events, arbitrariness should be eliminated. Unfortunately, however, historical data is not available in the case of LNG operations and extrapolations must be made using existing data on large ocean going vessels.

A generalized study was performed based on an event tree model of the sequence of occurrences following a tanker accident.[7] The four events were spill and generation of vapor at a given rate, dispersal and mixing of vapor with air, ignition and burning of the flammable mixture, and death of all persons within the flammable plume. The possible chain of events and consequences following an LNG spill appear in Figure 14.

It was assumed that the flash burning of the vapor plume would be the most important mechanism causing fatalities and was the only mechanism treated. The number of fatalities was assumed to be a function of the product of the ground area covered by the flammable portion of the plume at the moment of ignition, A, and the population density at the site of the spill. Mathematically, this is expressed:

No. of fatalities = $f(A)(P)$.

The ground area covered by the flammable portion of the plume at the moment of ignition, A, is a function of the vaporization rate, Q, the dispersion of the vapor, V, and a parameter relating flammable plume area and ignition, I.

Thus, probability of occurrence of any accident sequence (Fig. 14) is the joint probability of the parameter values:

Probability = $P(Q) \circ P(V) \circ P(I) \circ P(p)$

To obtain an upper limit, the frequency of accidental spills was assumed to be the same as for petroleum tankers. Based on this, it was assumed LNG tankship losses would be of two types: a leak of 1,000 bbl/hr or a rupture resulting in an instantaneous loss of the volume of one tank, 25,000 cu.m. The average annual loss rates for LNG tankers was found to be 0.03 losses/year for leak situation and 0.02 losses/year for instantaneous loss situation.

The consequent fatalities and their frequency were calculated for all the combinations of the values of the variables shown in the event tree diagram (Figure 14).[7] The frequency of accidents with a number of fatalities within a three-fold range were summed. The results in the form of a histogram of accident frequency versus fatalities/accident appear in Figure 15. Table 60 lists the expected fatalities per accident and their frequency of occurrence. The predicted statistical fatalities are 0.4/year for 1000 tankers annually calling at U. S. ports during the 1980-1985 time period. The projections represent an upper bound since they are based on a number of conservative assumptions. The most significant assumption was that there would be no collision

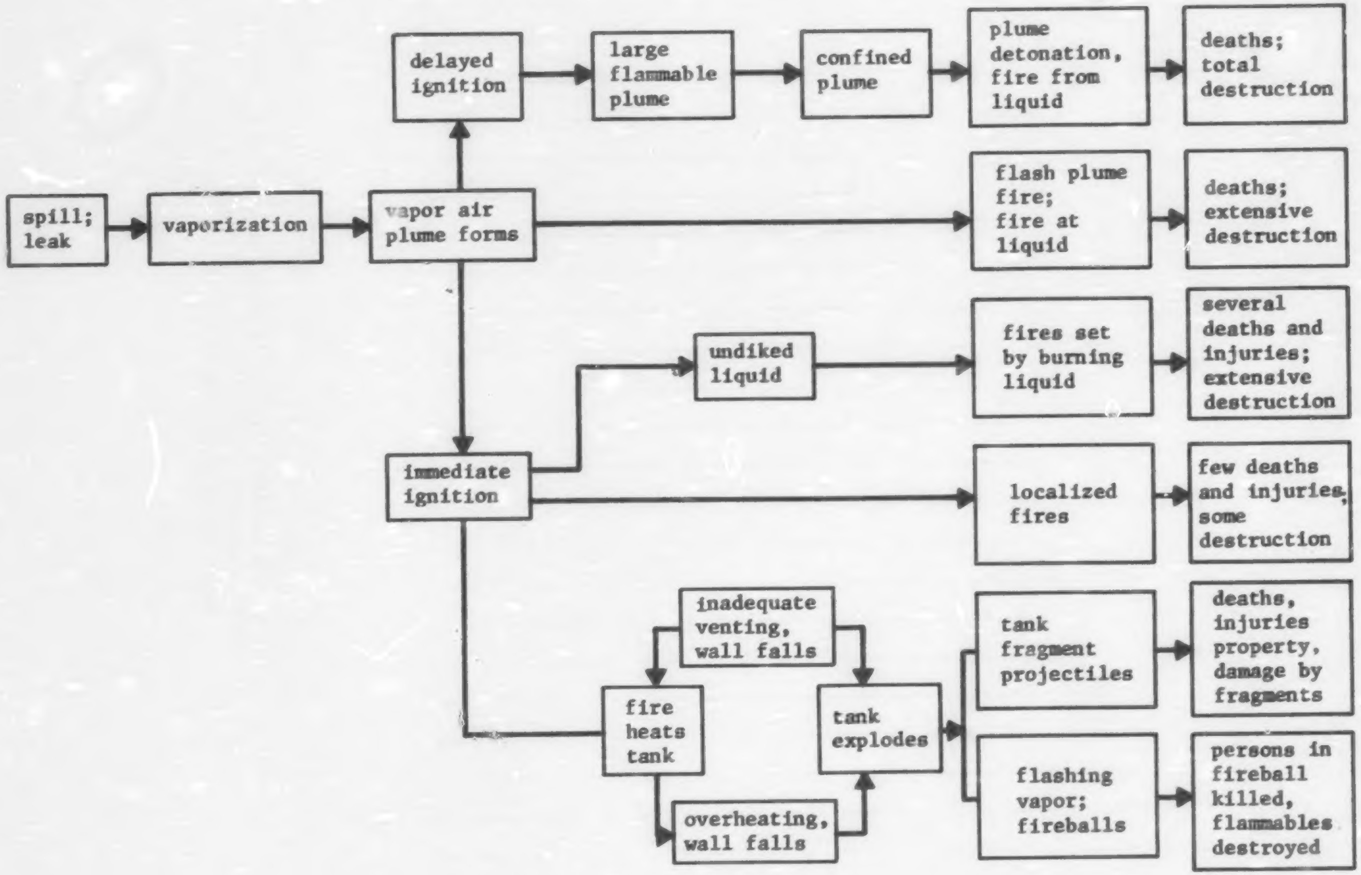
spill; leak
vaporization
vapor air plume forms
delayed ignition
large flammable plume
confined plume
plume detonation, fire from liquid
deaths; total destruction
flash plume fire; fire at liquid
deaths; extensive destruction
immediate ignition
undiked liquid
fires set by burning liquid
several deaths and injuries; extensive destruction
localized fires
few deaths and injuries, some destruction
inadequate venting, wall falls
fire heats tank
overheating, wall falls
tank explodes
tank fragment projectiles
deaths, injuries property, damage by fragments
flashing vapor; fireballs
persons in fireball killed, flammables destroyed

Figure 14. Event chain for LNG spills.[a]

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[a] Reference 7

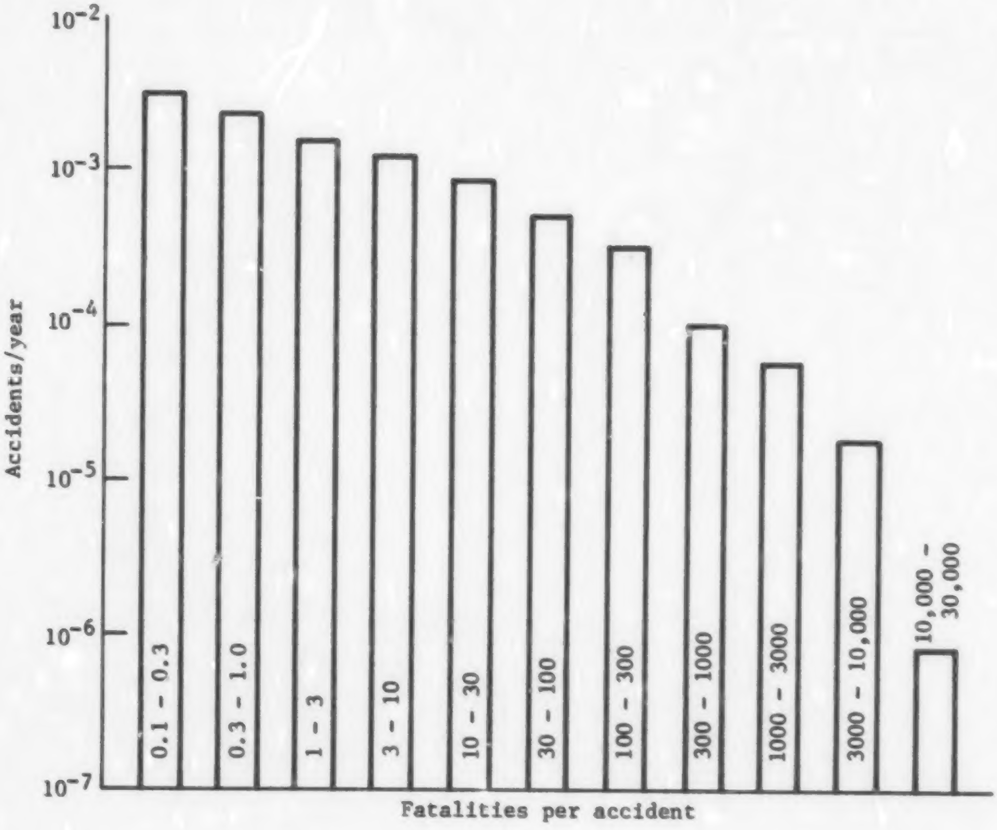

Figure 15. LNG tankship accidents assuming 1000 tankships per year; predicted frequency of classes of accidents with a statistical number of fatalities.[a]

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[a] Reference 7

TABLE 60 - PREDICTED FREQUENCY OF FATAL LNG TANKSHIP ACCIDENTS IN U.S. PORTS BASED ON 1,000 TANKSHIP TRIPS TO THE U.S. IN 1980[a]

Fatalities Per Accident	Frequency (per year)	
	Leak	Tank Rupture
0.01-0.03	3.5×10^{-3}	-
0.03-0.1	4.9×10^{-3}	-
0.1 -0.3	1.6×10^{-3}	2.0×10^{-3}
0.3 -1.0	1.2×10^{-3}	1.6×10^{-3}
1.0 -3.0	7.3×10^{-4}	1.3×10^{-3}
3.0 -10	4.3×10^{-4}	9.0×10^{-4}
10 -30	1.7×10^{-4}	6.2×10^{-4}
30 -100	3.3×10^{-5}	3.8×10^{-4}
100 -300	1.2×10^{-6}	2.2×10^{-4}
300 -1,000	-	1.1×10^{-4}
1,000 -3,000	-	5.6×10^{-5}
3,000 -1×10^4	-	1.8×10^{-5}
1×10^4-3×10^4	-	7.4×10^{-7}

---

[a] Reference 7

protection provided by double hull structure. Consequently, the probabilities may be twice as large or one one-hundredth as large as shown.

Risk measurement in the marine phase involves the probabilities of a ship collision and tank rupture and spill, and the effects of an immediate pool fire or delayed ignition of a plume. Phillipson presented a comparison of three models for three possible locations of LNG terminals in California.[8] The three sites under consideration were Los Angeles, Oxnard, and Point Conception. The models were developed by the Federal Power Commission (FPC), Science Applications, Inc. (SAI), and the El Paso Alaska Company (EAC). The probabilities, conseuqences, and resulting public risks are shown in Table 61.

Variations in the results of the studies are the consequences of different assumptions and modelling procedures. SAI considered only collisions as responsible for vessel casualties whereas the FPC and EAC considered rammings and groundings to have considerable impact. SAI considered separately one and two tank spills, FPC treated only the two tank possibility, and EAC considered only one tank spills and tanks of smaller capacity.

SAI and FPC assumed a 10% chance of non-ignition at the time of a spill. EAC excluded the change of a plume being formed. Since the population was beyond the lethal radius of a spill pool fire, no fatalities could occur in the sequence considered by EAC. However, EAC's assumption of no plume formation is not credible.

Risk measurement in the terminal phase of LNG operations considers a land storage tank spill and a fire or formation of a large plume followed by ignition at a later time. Only SAI performed these estimates. Table 62 shows that the maximum expected public fatalities per year is 1×10^{-7} for all three sites.[8]

These tables are summarized in Table 63 for both marine and terminal operations. The fatality rates have been restated as rates per person exposed at the site. The disparity in the results of Table 63 indicate the imperfections and subjectivity unavoidable due to lack of data.

As previously stated, risk analysis may be performed by several methods, e.g., extrapolation from existing accident data for marine operations or modelling using event trees. The validity of these methods cannot be evaluated because accident data are lacking. Also, each risk analysis is based on different assumptions as to the probability and severity of individual events. Examples of this include whether rammings and groundings are as potentially harmful as collisions, the number of tanks which will rupture, and the chance of a formation of a plume and later ignition versus immediate ignition of a pool.

TABLE 61 - PROBABILITIES AND CONSEQUENCES OF MARINE PHASE ACCIDENTS[a]

	Los Angeles		Oxnard		Point Conception		
	SAI	FPC	SAI	FPC	SAI	FPC	EAC
Casualties Per Year[b]	10^{-5}-10^{-2}	1.1	10^{-5}	2.5	10^{-5}	2.5	-
Probability Per Year of One-Tank Spill[c]	10^{-6}-10^{-3}	-	10^{-6}	-	10^{-6}	-	10^{-6}
Probability Per Year of Two-Tanks Spill	10^{-7}-10^{-4}	10^{-3}	10^{-7}	10^{-4}	10^{-7}	10^{-4}	-
Probability of Pool Fire, Given Spill	0.90	0.90	0.90	0.90	0.90	0.90	1.0
Probability of Plume and Delayed Ignition, Given Spill	0.10	0.10	0.10	0.10	0.10	0.10	0.0
Total Expected Public Fatalities Per Year[d]	10^{-3}	2	10^{-3}	0.3	10^{-6}	0.02	0

[a] Reference 8

[b] SAI considers only collisions and in several areas of port; FPC and EAC also consider rammings and groundings.

[c] 37,500 m^3 per tank for SAI and FPC; 24,500 m^3 for EAC.

[d] SAI values presented estimated by author from SAI data in different form; 1990 population forecasts and 565 LNG vessel trips per year assumed.

TABLE 62 - LAND SPILL PROBABILITIES AND TOTAL FATALITY RATES[a]

Los Angeles

Initiating Event	Ship Tank Sidewall	Land Tank and Dike	Transfer Components
Internal Failure	10^{-11}	-	10^{-3}
Earthquake	-	10^{-14}	10^{-12}
Meteorite	10^{-9}	10^{-8}	10^{-8}
Aircraft	10^{-6}	10^{-6}	10^{-3}
Missile	10^{-7}	10^{-9}	10^{-7}
Fill Factor[b]	10^{-1}	10^{-1}	-
Total at Site	10^{-7}	10^{-7}	10^{-3}[c]

Maximum Expected Public Fatalities Per Person Per Year -- 10^{-7}

Oxnard

Initiating Event			
Internal Failure	10^{-11}	-	10^{-3}
Ship Collision at Dock[d]	10^{-6}	-	-
Earthquake	-	10^{-17}	10^{-4}

[a] Reference 8

[b] Fill factor approximately summarizes the effects of SAI's assumptions that ship or land tank will generally be only partly filled at any given time, and that a rupture may occur at a position on the tank above the level of its contents.

[c] But multiplied by SAI by 10^{-11} to reflect capability to isolate the spill.

[d] Considered by SAI for Oxnard only.

(continued)

TABLE 62

(continued)

Oxnard (continued)

Initiating Event	Ship Tank Sidewall	Land Tank and Dike	Transfer Components
Meteorite	10^{-9}	10^{-8}	10^{-7}
Aircraft	10^{-6}	10^{-6}	10^{-4}
Missile	10^{-6}	10^{-9}	10^{-6}
Fill Factor	10^{-1}	10^{-1}	-
Total at Site	10^{-6}	10^{-7}	10^{-3}[c]

Maximum Expected Public Fatalities Per Person Per Year -- 10^{-7}

Point Conception

Initiating Event			
Internal Failure	10^{-11}	10^{-6}	10^{-3}
Earthquake	-	10^{-5}	10^{-4}
Meteorite	10^{-9}	10^{-8}	10^{-8}
Aircraft	10^{-7}	10^{-6}	10^{-4}
Missile	10^{-7}	10^{-9}	10^{-7}
Fill Factor	10^{-1}	10^{-1}	-
Total at Site	10^{-8}	10^{-6}	10^{-3}[c]

Maximum Expected Public Fatalities Per Person Per Year -- 10^{-7}

TABLE 63 - ESTIMATED EXPECTED PUBLIC FATALITIES PER EXPOSED PERSON PER YEAR[a]

	Los Angeles		Oxnard		Point Conception		
	SAI	FPC	SAI	FPC	SAI	FPC	EAC
Marine Operations[b]	10^{-7}	10^{-4}	10^{-8}	10^{-6}	10^{-9}	10^{-5}	10^{-8}
Terminal Operations	10^{-7}	-	10^{-7}	-	10^{-7}	-	-
Total Expected Public Fatalities Per Person Per Year	10^{-7}	10^{-4}	10^{-7}	10^{-6}	10^{-7}	10^{-5}	10^{-8}

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[a] Reference 8

[b] Only SAI gives individual or per person fatality rates. For the FPC and EAC, a proportionating of their total numbers of fatalities per year of 0.02 and 10^{-5}, respectively, has been carried out by the author to give the individual fatality rate estimates shown.

SECTION 7.0

HYDROELECTRIC

7.1 RESOURCE SYSTEM OVERVIEW

Since the first water mills were made operational over 3,000 years ago, man has looked to water as a source of energy. Recognition of this potential source would be expected as the energy of a rushing body of water is apparent by visual examination. It was not until the 1880's, however, that water power was utilized to generate electrical energy. The first plant opened on September 30, 1882 and utilized the power of the Fox River in Appleton, Wisconsin, producing direct current (DC). A plant was established on the Willamette River in Oregon using a more efficient means of transmitting electricity by generating alternating current (AC). By 1940, approximately 30% of the electricity generated in the United States was by hydroelectric plants. Because of increased use of fossil fuels and greater demand for energy, this percentage fell to about 15% by 1971.

There are many positive aspects to hydroelectric power generation. These include low cost of operation and maintenance, low downtime, and multiple use benefits. For example, the downtime has been shown to be approximately one quarter that of steam electric generating plants, or about 3% per year. The low downtime for hydroelectric power plants is indicative of the infrequency of major accidents affecting power production. Some multiple use benefits include navigation, flood control, irrigation, public water supply, and recreation.

There also are several drawbacks to use of hydroelectric resources. These include high capital costs, long transmission distances due to remoteness, irreversible environmental effects, and the variability of river flow. That this last factor can be overcome was demonstrated at Hoover Dam, with Lake Mead capacity equal to 2 years of river flow. However, the greatest drawbacks to hydroelectric power generation are the limited availability of suitable damming sites and flooding of habitable lands when dams are built.

In 1972, the total power generating capacity in the United States was 418 x 10^3 MWe (megawatts of electricity) of which 57 x 10^3 MWe (14%) was contributed by hydroelectric power.[9] Estimates of hydroelectric capacity in the U.S. are derived by the U.S. Geologic Survey from their stream-flow data. The data indicates both significant installed and potential hydroelectric capacity in the western United States. The North Pacific area accounts for more than one-third of the total U.S. developed and undeveloped capacity. One source estimates that theoretically the United States can produce 390 x 10^3

MWe; however, various problems probably reduce this figure to 179 x 10^3 MWe.[15] Another source estimates potential hydroelectric power generation at 186.8 x 10^3 MWe.[81] Using this figure, it can be concluded that in 1972, approximately 30% of our estimated hydroelectric energy capacity was installed generating capacity. This energy was produced in 1,511 plants throughout the country. Even if our hydroelectric potential was developed to full capacity, it would still be unable to supply our total energy needs. However, this energy source of extremely low pollution, could considerably reduce our needs with respect to other energy alternatives such as fossil fuel and nuclear plants.

Hydroelectric power derives its energy from the potential and kinetic energy available in the water source. The potential energy is a function of the elevation or head of water above the turbine, and the kinetic energy is dependent upon the flow rate. The available energy can be expressed in terms of an energy head per unit mass, h_e according to the following relationship:

$$h_e = z + \frac{v^2}{2g}$$

where z = elevation of the water surface above a reference
v = mean velocity of the water
g = acceleration of gravity

A hydroelectric power plant is therefore configured to readily convert potential energy to kinetic energy and to thus take maximum advantage of the resource. A pictoral representation of a hydroelectric power station is shown in Figure 16.

The plant consists of four basic components, the reservoir (forebay), water conduit (penstock), hydraulic turbines, and exit raceway (tailrace). The electrical system on the output side of the turbine, such as generation, transformers, transmission lines, etc., is similar to the generation equipment at power plants using any of the resources (fossil, geothermal).

The reservoir serves as turbine feed water storage as well as providing sufficient head above the turbine so as to achieve the maximum energy head. Storage is required during reduced plant load so that the water may be used for peak load periods and to compensate for low and variable stream and river flows. Reservoirs are created by building a dam across a natural basin, through which the water source flows, flooding the basin. Hydroelectric dams generally are permanent structures built from solid or hollow gravity type concrete. Other types of dams are buttressed concrete, timber and steel (rarely used in the United States), earth, rock fill (generally used in remote locations), and the arch.[82] It is generally difficult to find suitable sites for the arch type. Among its requirements are a small length to height ratio and valley walls composed of good rock which can resist end thrust.

A reservoir may have a depth of over 400 ft., and encompass approximately 247 sq. miles. The Hoover Dam structure at the head of Lake Mead is 726 ft. high (2nd highest in the U.S.) and 1,244 ft. long. The longest dam constructed was the Amistad on the Rio Grande in 1969 at 3,202 ft., although its height is only 285 ft. The dam method of managing the water resource is generally used in medium-to low-head projects. In some cases smaller regulating

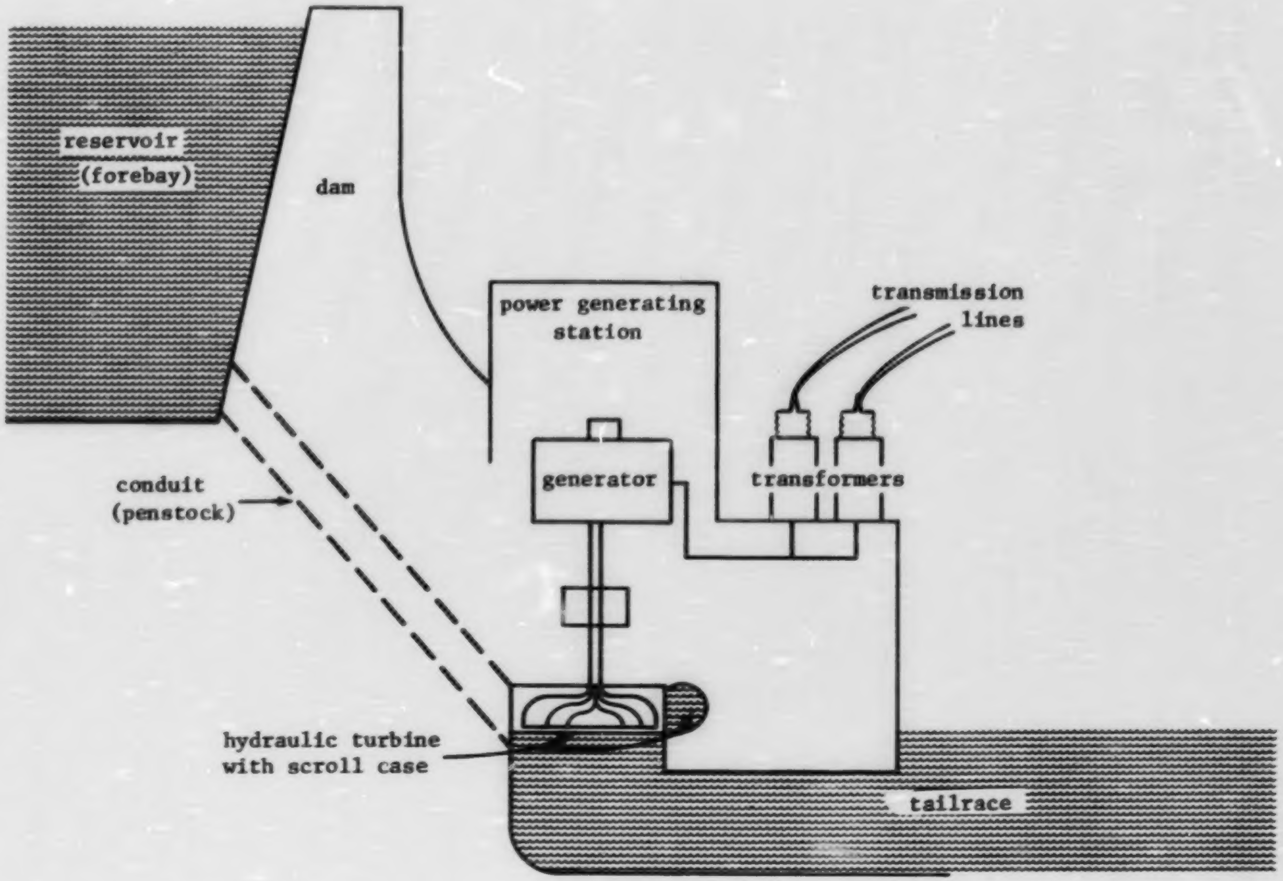

reservoir
(forebay)
dam
power generating
station
transmission
lines
generator
transformers
conduit
(penstock)
hydraulic turbine
with scroll case
tailrace

Figure 16. Typical hydroelectric power plant.

reservoirs are used to take advantage of smaller heads. In high- to medium-head projects part or all of the flow is diverted, through tunnels for example, to take advantage of steep gradients along a river. Short- or long-term holding storage reservoirs may be used in such a system.[83]

The penstock is the conduit between the dam intake and the turbines in the powerhouse. This conduit may be divided into nonpressure and pressure types, the former following the hydraulic gradient, the latter being well below it and leading to the turbine. The nonpressure conduit may be canals, flumes, and pipe, while the pressure conduit is usually steel pipe. In low head plants the conduit is the dam structure.[84] Flow in and out of the conduit are controlled by gates and valves at either or both ends.

The turbine generator system uses three types of driving machinery - propeller turbines, inward flow pressure turbines, and Pelton wheels. These hydraulic turbines are divided into two classes - impulse type, which use the kinetic energy of a high velocity stream acting on the circumference; and the reaction type which uses the combined pressure and velocity of the jet, filling the runners and water passage within. The impulse units are generally used at heads exceeding 800 ft. and the jet of water freely discharges and strikes buckets located around the runner, such as with the Pelton wheel. The propeller and inward flow pressure turbines are the reaction type, with the water passing through and filling the vanes and passages. The discharge from an impulse turbine freely enters the tailrace at atmospheric pressure, while the closed loop system of the reaction turbine has in integrally designed draft tube which connects the turbine outlet to the tailrace without disturbing the pressure flow regime. The tailrace is the passage by which the discharge water exits the turbine and reenters the lower portion of the river or stream.

In the case of anticipated, rapid-fluctuating peaking power needs, a pumped-storage system is used which consists of a pumping unit and an elevated reservoir. In non-peak hours the output of the hydroelectric plant is used to drive pumps to lift water back up to an elevated reservoir for storage. At peak hours the steep gradient can be used in providing additional hydroelectric power. These storage basins can also be used to feed lower reservoirs if required by low flow or draught conditions.

7.2 ACCIDENT OVERVIEW

This section will consider accidents associated with hydroelectric power as an energy source, limiting the discussion to those events which occur in the system from the reservoir (forebay) through the turbine. The generator is not included in this discussion because it is similar to the electric generation system for most other energy sources and is covered in Section 11. Table 1 shows representative major and minor accidents related to the hydroelectric system.

The most severe accident involves a dam failure which occurs infrequently. While there have been a number of dam breaks, only one major hydroelectric dam has failed in recent years. The Teton Dam, located on the Teton River in

Idaho, failed catastrophically in June, 1976. Constructed in 1972, at an estimated cost of $65 million, it had an intended estimated capacity of 20,000 KW. The breaching of the dam caused an estimated $500 million in damage in the upper Snake River valley, spreading water over 300 sq. miles. It caused the evacuation of an estimated 30,000 people, killed 9 with 8 missing, while destroying 13,000 cattle. The cause of failure may have been water penetration of a curtain of grouting (cement based filler) on the dam, compounded by possible soil instability and improper construction practices; however, a final report on the dam failure has not yet been released by the Department of the Interior.

Among the causes of failure for a solid gravity concrete dam are sliding on a horizontal joint above the foundation, on the foundation, and overturning on a horizontal joint within the dam, at the base of the dam, or at a plane below the base. Additional causes of failure can include erosion below spillways leading to undermining, and forces exceeding anticipated design for such items as water pressure, ice pressure, earth pressure, weight of the dam, weight of the foundation, earthquake forces, and reaction of the foundation.

A dam failure can cause both direct and secondary events which are detrimental to the environment. Among these are the inundation and decimation of biological species, destruction of food supplies, loss of topsoil permitting erosion and the loss of ground cover, and contamination of food and water supplies.

A severe loss of water without dam failure can occur because of seepage. Serious losses can occur if the dam is on a porous foundation or in long, unlined canals. In an arid region, the absence of rock formation, a water table at considerable depth, and a previous foundation can cause a loss of as much as 30%.[85] Careful planning and geologic surveying can eliminate this occurrence.

Overflow of a dam, caused by spillway failure, heavy rains, or a rapid thaw may lead to a dam burst. Leaks which may occur would cause minor damage. In the case of an earth dam, overflow (overtopping) generally leads to failure.

Within the hydroelectric plant there can be several types of accidents most of which are minor and infrequent. However, a major accident which can occur is inundation of the plant. This can be caused by conduit failure, overtopping of hydraulic structures, extreme river flow conditions, or through conventional openings within equipment. The result would be to remove the turbine from service and cause extensive damage to electrical circuits and equipment including the generator.

An example of an unusual environmental accident resulting from a dam burst, other than the expected drowning and inundation, occurred in Chino-Farm, Maryland in March of 1972. There was a kill of 2000 geese, of which 88% were found to have died of lead poisoning. It was found that the geese were exposed to lead in mud highly contaminated with buckshot. This mud flat resulted from the draining of a pond caused by a dam burst. This type of accident is expected to be rare. In addition, an electrical fire may occur from partial flooding causing extensive plant damage. This type of accident has occurred but is infrequent.

Conduit failure may be caused by a number of factors among them corrosion and cavitation erosion. Technological advances based on analysis of past accidents have reduced the frequency of such accidents.

Interruption of power can occur through accidents in the generator and transmission systems (discussed in the Section 11) or through turbine failure. Previous statistics demonstrated that the downtime for a hydroelectric station amounted to an average of 2 days per year plus normal maintenance time, or approximately one fourth that of steam electric plants. The downtime, although not documented, is probably due to mechanical malfunction in the turbine or valves. Bearings and the other parts of such operating equipment can fail under stress or through poor maintenance.

Personnel accidents are probably the most frequently occurring events in the industry, involving construction, maintenance, and normal operations. A survey of four types of power plants (coal, oil, hydroelectric, and nuclear) indicates that for a hydroelectric plant the occupational injuries occur at approximately one half the frequency and with one-tenth the severity of the average for all electric generating plants.[86] The survey, covering 1969-72, included 4 companies with an exposure of 1,711,776 manhours. The frequency reported was 4.1 disabling work injuries per 1 million employee-hours exposure. One hundred forty nine total days were lost for work injuries per 1 million employee-hours exposure. The results for 1972 are not verifiable because they involved confidential data and data extrapolated from those of the electric utilities industry in general.

SECTION 8.0

GEOTHERMAL

8.1 RESOURCE SYSTEM OVERVIEW

The geothermal resource reflects the thermal energy represented by the temperature distribution within the earth's interior over the range between very high temperatures at the molten core and mild temperatures prevailing at the habitable surface. The existence of this wide temperature distribution manifests itself periodically through the eruption of volcanoes and the formation of new land masses. The temperature distribution pattern is not a uniform one. Higher temperatures approach the surface closer in locations where the earth's crust is younger and less stable, making the easiest access to the high temperature zones in the geographic areas which are subject to earthquakes and volcanic activities. These areas are shown in Figure 17.[85]

Accordingly, the areas having the easiest access to the geothermal resources are: Italy, New Zealand, United States, Iceland, Japan, Soviet Union, Hungary, Mexico, El Salvador, Kenya, Ethiopia, Phillipines, Indonesia, Chile, Guadaloupe, Taiwan, and Turkey. These are the countries where significant activity to exploit the resource has occurred.

The earliest commercial use of geothermal energy for the generation of electricity occurred in 1913 in Larderello, Italy. Later, between 1928 and 1933, a municipal district heating service from geothermal hot water aquifers was installed in Reykjavik, Iceland. In 1940, individual hot water wells began to be used for heating purposes in New Zealand. The first 0.001 MW experimental generating plant in Japan, built in 1924, grew to a 0.02 MW plant in 1951. Japanese activity currently is aimed at a goal of 60 MW, and district and greenhouse heating-systems exist.

Currently, the Italian installations generate 415 MW total. New Zealand generation is about 220 MW, with large use of steam and hot water for heating. The district heating system in Reykjavik now serves 90% of the homes. About 60% of the population of Iceland is served by some form of geothermal heat including the heating of greenhouses to raise fresh vegetables.

The first unit for electricity generation in the United States was installed in 1960 at the Geysers in northern California. This unit had a capacity of 125 MW. By 1972, the total installed capacity had grown to 302 MW. The Geysers presently is producing 522 MWe, and is projected to reach more than 2000 MWe at maximum development, around 1985.[86]

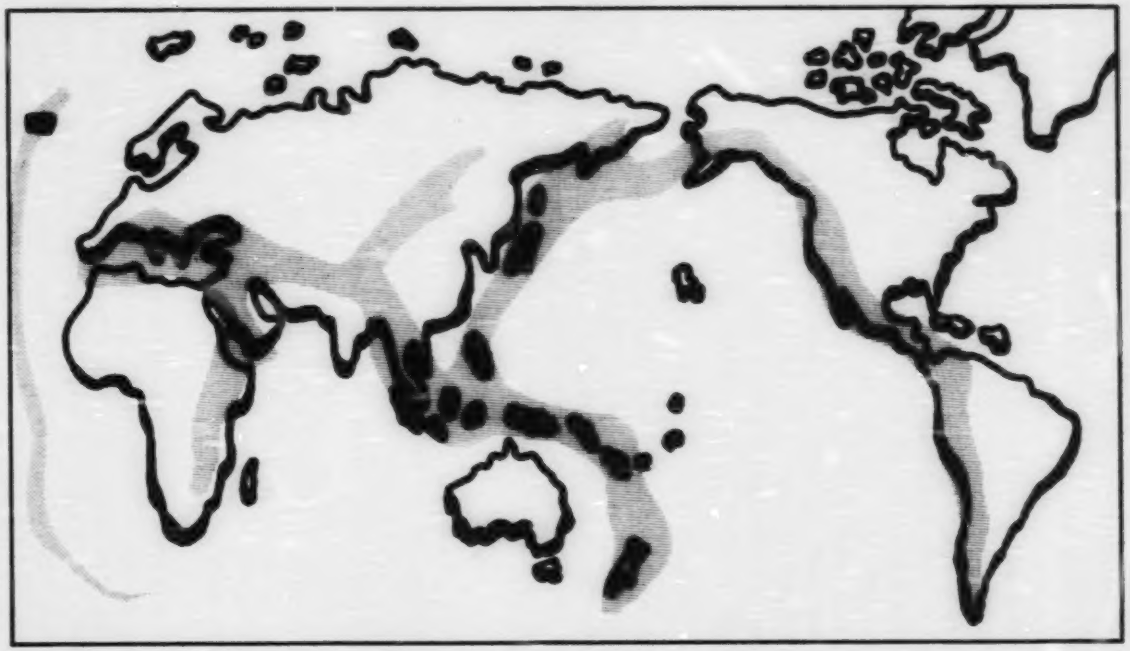


Figure 17.

Regions of intense geothermal manifestations.

Source: P. 16, Kruger, P. and Otte, C. "Geothermal Energy" Stanford University Press, Stanford CA. (1973)

Geothermal manifestations in the United States occur as three systems which have been described by the United States Geological Survey[87] as:

1. Hydrothermal convection systems,
2. Hot igneous systems, and
3. Conduction dominated areas (geopressured zones).

Hydrothermal convection systems involve a fluid, usually water, which is heated by convection from the surrounding rock. If the convection and water flows are such that the water is largely vaporized when extracted, the system is vapor dominated and the resource can be recovered as dry or wet steam. If the fluid is recovered as a mixture of steam and water, the resource is called liquid and exists at temperature levels ranging from above 150°C to below 90°C. Hot igneous systems involve masses of rock which may be molten in part and exist at temperatures above 650°C. Conduction-dominated areas involve underground aquifers or sedimentary basins which have been heated by conduction from the surrounding strata.

The exploitation of vapor-dominated geothermal resources has been demonstrated since 1960 in the United States with experience with the privately-owned and expanding electrical generation facilities at the Geysers in California. Programs to develop the potential of the other geothermal resource types have been formulated and are being implemented by the Energy Research and Development Administration (ERDA). A forecast of the growth of geothermal electrical generation capacity in the United States through 1986 is shown in Figures 18 and 19.[88] This forecast is based on one scenario for development of a research, development, and demonstration program. The current Federal program is attempting to achieve the power on line goals in this range. Thus, from the current generation capacity in California of about 500 MW, electrical generation capacity from all geothermal manifestations is forecast to grow to about 3000-4000 MW total by the mid 1980's.

8.1.1 Resources

The hydrothermal and hot-igneous resource systems predominate in the western United States and Alaska. The single conduction-dominated area discovered to date is the coastal areas of Texas and Louisiana. Measurement of geothermal reserves is based on the following definitions:

- Geothermal Resource Base. The base is the total stored thermal energy in rock strata above 10 km (6.25 miles) depth, measured above 150°C.

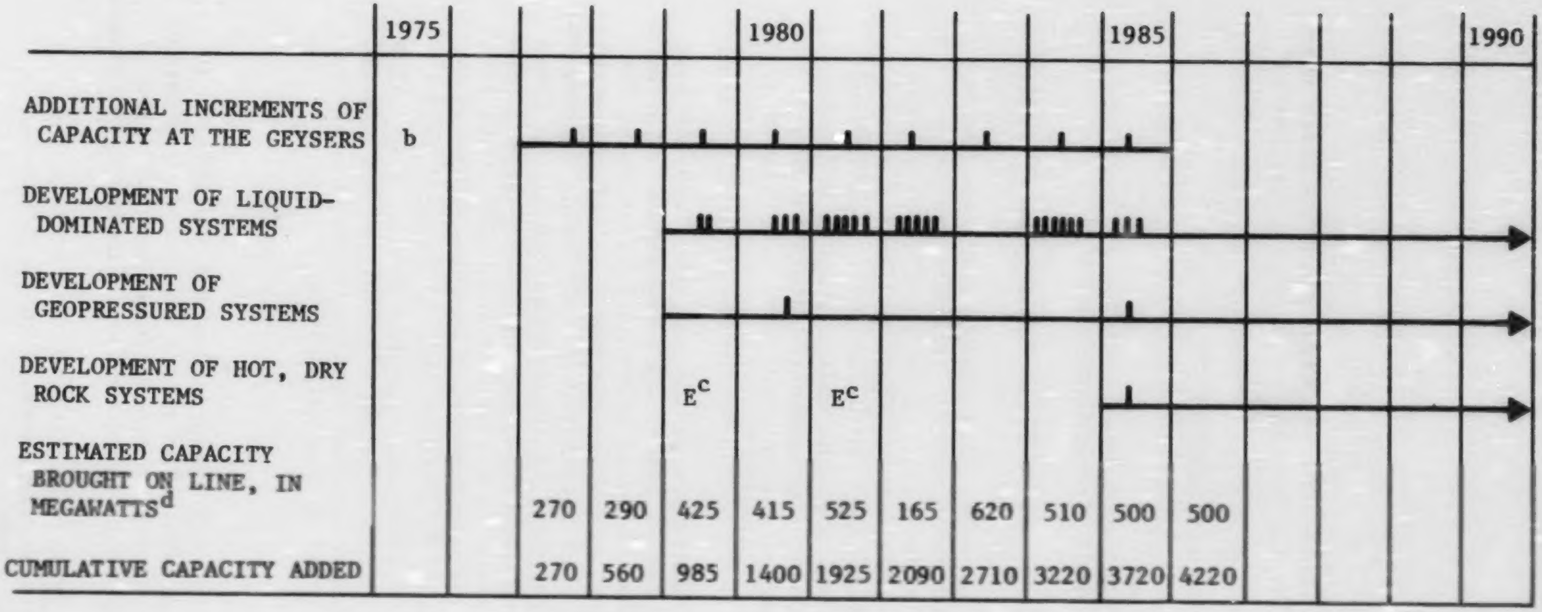


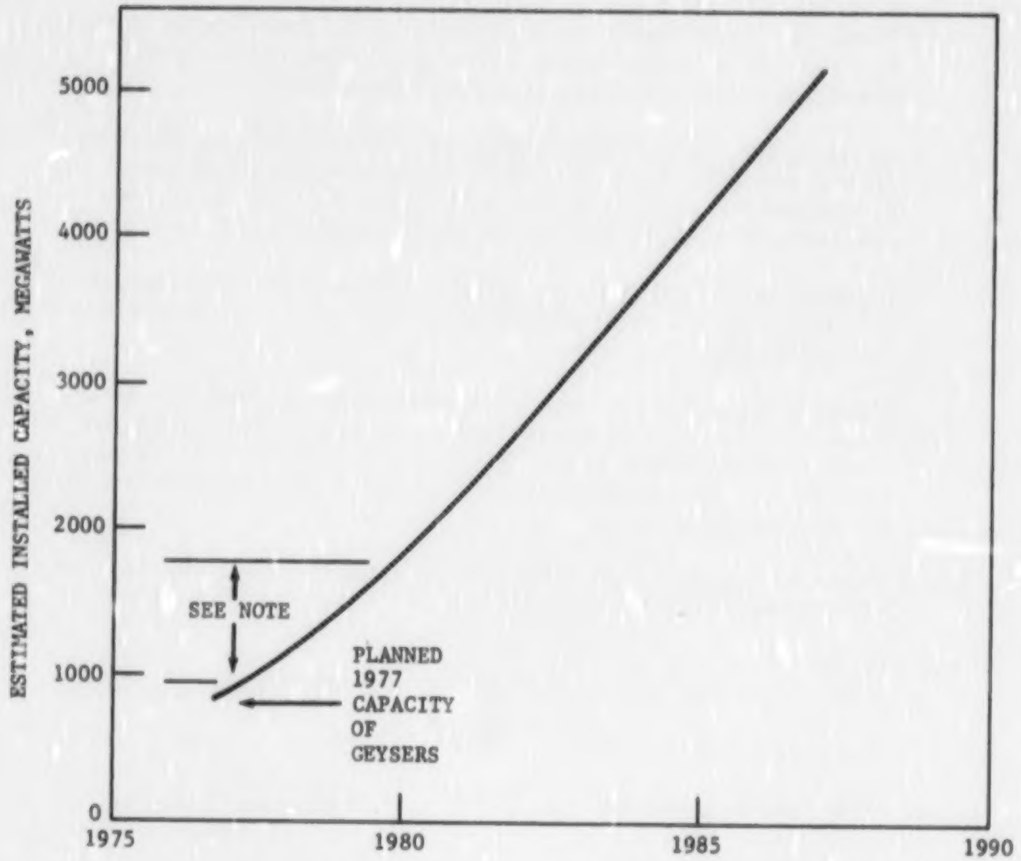
Figure 18. Near-term scenario for geothermal energy development.[a]

[a] Reference 88

[b] Each tick represents one plant brought on line

[c] E denotes a thermal extraction experiment

[d] Estimates not available beyond 1987



NOTE: GROWTH THROUGH 1980 IS CHIEFLY FROM ADDITIONS TO THE GEYSERS, PLUS EARLY IMPERIAL VALLEY INSTALLATIONS

Figure 19. Estimated national growth of geothermal electric power.[a]

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[a] Reference 88

- Geothermal Reserves. The geothermal reserves are those portions of the resource base from which useful energy forms are recoverable at a cost which is competitive with the cost of similar energy forms now commercially produced, and available at comparable locations.

- Paramarginal Geothermal Resources. These are the portions of the resource base from which useful energy forms are recoverable at a cost which is between one and two times the cost of similar energy forms now commercially produced.

- Submarginal Geothermal Resources. These are the portions of the resource, recoverable at a cost more than two times current commercial costs.

- Megawatt-Century. A unit of measurement of reserves in terms of electricity production. It is the generation of 1 megawatt of electricity for 1 century, or for 875 thousand hours; or the generation of 1 kilowatt of electricity for 875 million hours.

The estimated reserves for the high-temperature hydrothermal convection system (temperatures above 150°C) are the following:

Identified Reserves (measured and inferred)	3500 Megawatt-Centuries
Paramarginal Resources	3500
Submarginal Resources	+1000
Undiscovered	
Resources	38,000 Megawatt Centuries

The reserves at the Geysers are estimated at 477 megawatt-centuries or 1590 megawatts over a 30 year period. For the intermediate-hydrothermal convection system, the U. S. Geological Survey estimated the resource base to be 345×10^{18} calories or 137×10^{16}BTUs. There was no technological or cost basis for distinguishing between paramarginal and submarginal resources. No estimates were provided for the low-temperature hydrothermal system (temperatures below 90°C).

The U.S.G.S. conservatively estimated geothermal resources of hydrothermal convection systems at 11,700 MWe of potential generating capacity from identified U. S. reserves. Their conservative estimate of the exploitable geothermal resources, those which are discovered and undiscovered, is 153,400 MWe or approximately one-third of the present 450,000 MWe power requirements. Mueller[89] indicated that geothermal energy from untapped sources in the U. S. are estimated at 8×10^{26} calories of approximately 5,600 trillion barrels of oil.

Reserve estimates are not practical to make for hot igneous systems because demonstrated extraction technology and the associated cost basis do not exist. For partially molten igneous systems no techniques have been developed to penetrate high temperature molten areas (above 650°C) and to emplace devices for extracting thermal energy and bringing it to the surface. Good estimates of reserves of hot dry rock systems also are not available.

Reserve estimation for conduction-dominated areas, namely the coastal zone identified for Texas and Louisiana, is complicated by the fact that the water contained in the sedimentary layers is overpressured (i.e., the water exists at pressures in the order of 11-14,000 psi at depths of 4-6km, pressures far greater than equivalent hydrostatic pressure), and contains dissolved methane, itself an energy source. The Geological Survey estimated the reserves on the basis of independent geopressure-energy recovery, geothermal energy-recovery, and methane recovery. Three plans for reserve estimation were evaluated. The resource and reserves estimated are shown in Table 64.[90]

8.1.2 Technology

Geothermal technology is used to produce useful forms of energy from geothermal resources, i.e., forms that are readily marketable. Such forms are the following:

- Electricity. Dry-steam flow from a high-temperature hydrothermal system such as at the Geysers is already used to produce electricity in the United States. This energy form would most likely be produced from exploitation of dry-hot-rock hot igneous systems.

- Hot water for district heating, agricultural and industrial process uses. The geothermal resource is the intermediate and low-temperature hydrothermal systems. District heating systems are already installed and operating at Klamath Falls, Oregon, and in some other locations in the Western United States.

- Multiple energy forms. In conduction-dominated areas, such as coastal Texas and Louisiana, a mix of electricity and pipeline gas could be produced.

The function that must be performed by geothermal technology are exploration, resource production, conversion, and disposal or injection

TABLE 64

RESOURCES AND RESERVES

GULF COAST CONDUCTION-DOMINATED GEOTHERMAL AREA[a]

	Resource Base Equivalent Thermal Energy		Plan 1[c]		Plan 2[d]		Plan 3[e]	
	10^{18} Calories	10^{16} Btu	MW-cent	MW-20 yrs.	MW-cent	MW-20 yrs.	MW-cent	MW-20 yrs.
Thermal	10,920	435	24,380	121,900	38,140	190,700	5,690	28,450
Methane	6,030	239						
Mechanical	50	2	9,970	49,850	0	0	3,560	17,800
TOTAL	17,000[b]	676	34,350	171,750	38,140	190,700	9,250	46,250

[a] Reference 90.

[b] Revising this total on a labored pessimistic basis, it is still 9500 x 10^{18} calories (378 x 10^{16} Btu).

[c] Plan 1: 20 year life, during which well-head pressure gradually decreases to hydrostatic at end. Flow is limited to constant value throughout the life span. Surface subsidence could reach 15-20 feet.

[d] Plan 2: 20 year life, during which maximum well-head flow obtained with full reservoir pressure, surface subsidence could be even more significant.

[e] Plan 3: 20 year life, during which well-head pressure is increased and regulated to limit surface subsidence to 3 feet.

of the spent fluids. Once the resource is converted into marketable form, its transport and distribution could be handled by new or existing conventional installations such as high-voltage transmission lines in the case of electricity and high-pressure pipelines in the event natural gas is produced. In district heating applications, pipeline transport of hot fluid to the nearest population center and distribution pipelines within the center are required.

8.1.3 Exploration

The result of exploration is the discovery, delineation, and design of the extraction procedures for a geothermal reserve. Activities toward such an end can involve any or all of the following:

1. Airborne surveying for geological analysis and mapping of underground structures by topography and by measurement of magnetic fields and infrared radiation, if the area is relatively unknown structurally and stratigraphically.

2. Field exploration on the ground that could include observation of geological surface features and measurement of thermal manifestations, measurement of the water table in available wells, sampling and chemical analysis of water from hot springs and fumaroles, measurement of electrical conductivity, seismic noise, and heat flow, and active seismic exploration.

3. Drilling exploratory wells to determine temperature-depth distribution, pressure depth distribution, permeability-porosity, fluid composition, and stratigraphy.

8.1.4 Resource Production

The result of resource production usually is the supply of a steam or hot water stream suited to the intended method of energy conversion. In conduction dominated areas of the United States a stream of natural gas would be produced. Production, therefore, includes drilling and operating wells to bring reserves to the surface, treating effluents to remove unwanted solids or liquids, gathering individual sources into a common supply, and drilling and operating wells which may be needed for injection of waste fluids into the formation.

Well-drilling techniques are similar to those for oil and gas drilling, except for problems unique to geothermal resources. Extremely slow penetration rates may be encountered even with bits designed for hard rock. Heat and abrasiveness tend to produce high wear rates on subsurface equipment. Velocities in the annular spaces, when steam-water is encountered, can be sonic and lead to high erosion rates.

Air colled drill bits may need to be substituted for mud cooled. Particular attention needs to be given to casing and cementing the well.

Surface equipment consists of liquid/gas separators and gas/particulate separators. Wells are shut in only if their production is not required for a long period because substantial disturbance of well flow rates may result in entrainment of large solid particles which must be removed. Pipelines need to be protected against overpressure by relief valves and rupture discs when steam is not required, but the well is not shut-in.

For the dry-hot-rock hot igneous system resources, water would be injected into the formation and water would be brought to the surface. Figure 20 illustrates a potential technology for the recovery of hot water from dry-hot-rock formations. Appropriate hydraulic fracturing techniques would be needed in order to produce flow paths through the rock between the inlet well and the discharge well.

In the conduction-dominated area, well-head pressure would be let down at each well through a mechanical device that may or may not recover power before any collection of well-head effluents is attempted. Alternatively, kinetic and thermal energy would be recovered with "total flow" devices now in the experimental stage.

8.1.5 Conversion

Conversion technologies depend on whether the geothermal resource is produced as dry steam, hot water, or hot water and methane mixtures. Technology is well developed in the case of dry steam because of experiences at the Geysers and many years of experience in electricity generation. A low-pressure condensing turbine receives saturated steam at 113.7 psia and exhausts it at 2 psia into a direct contact condenser fed with water from a cooling tower. The non-condensible gases are ejected through a two stage ejector equipped with inter and after condensers. The steam rate may be 17.6 lbs. per kwh. Sufficiently hot (7200°C) liquid-dominated systesm can be operated similarly by allowing the fluid to flash to steam, though the flashing fraction decreases with decreasing temperature.

For intermediate temperature systems, which are liquid dominated, and in cases where steam could be unusually corrosive to the turbine components, (e.g., in the Imperial Valley, California), an indirect cycle operating at a lower level temperature difference than for a a direct steam cycle may be used. Figure 21 illustrates such a cycle based on isobutane. A 10 MW thermal test loop employing this principle is being operated at Niland, California. Water temperatures may range from 160°C to 200°C.

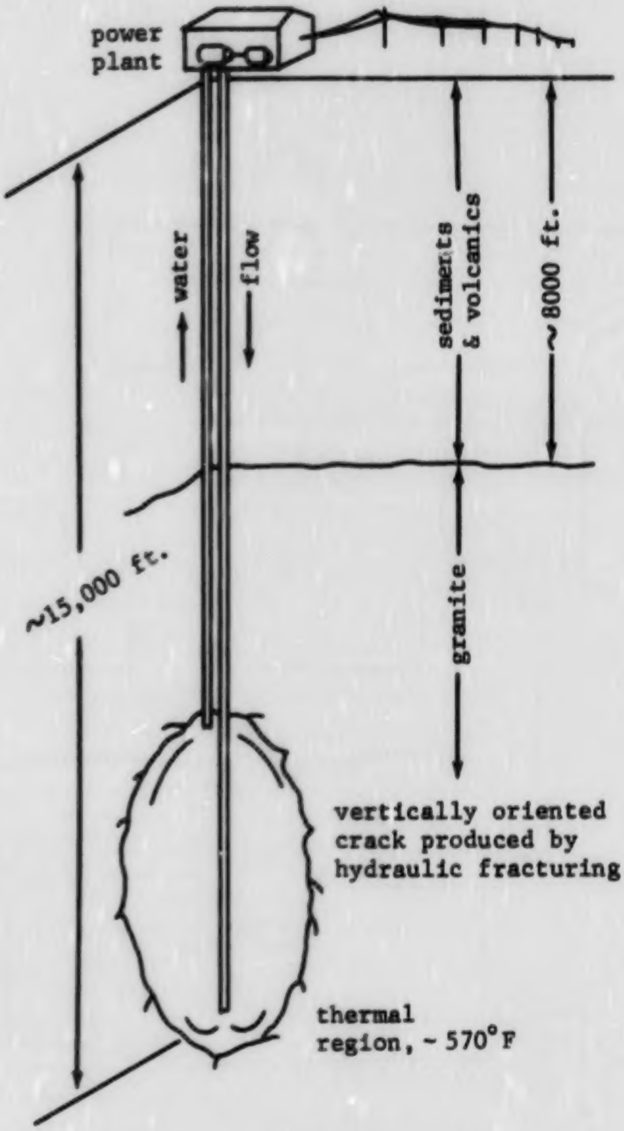
power plant
water
flow
sediments & volcanics
~8000 ft.
~15,000 ft.
granite
vertically oriented crack produced by hydraulic fracturing
thermal region, ~ 570°F

Figure 20.

Potential resource recovery system hot-dry-rock hot igneous system.[a]

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[a] Reference 1.

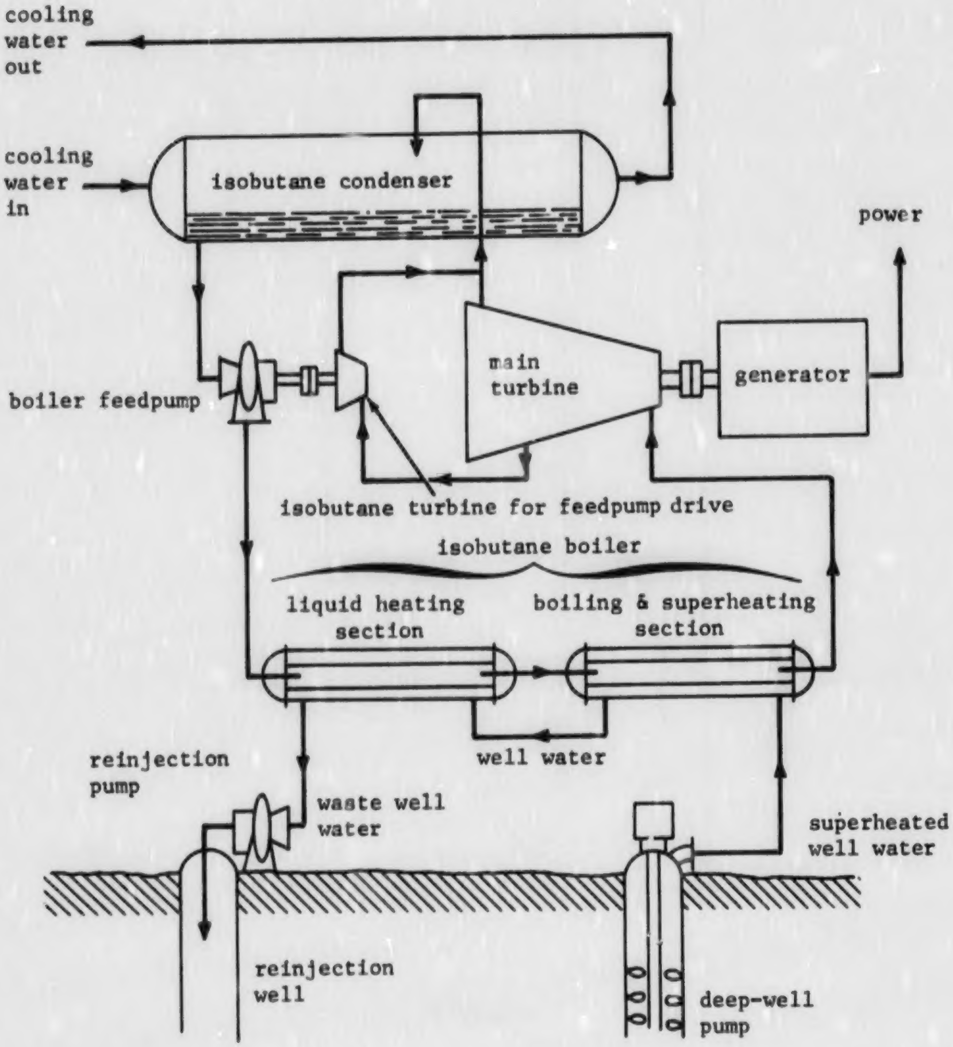
cooling water out
cooling water in
isobutane condenser
power
main turbine
generator
boiler feedpump
isobutane turbine for feedpump drive
isobutane boiler
liquid heating section
boiling & superheating section
well water
reinjection pump
waste well water
superheated well water
reinjection well
deep-well pump

Figure 21.
Vapor-turbine cycle diagram.[a]

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[a] Reference 98.

For the conduction-dominated area, the presence of dissolved methane in the geothermal water may require careful consideration of the turbine exhaust pressure because of the need to recompress the methane to pipeline pressures after condensation of the exhausting steam. It is unlikely that the methane would be burned for power production.

8.2 ACCIDENT OVERVIEW

The geothermal reserves discussed above are dispersed throughout the western part of the United States in terrain of widely varying character. It ranges from the densely populated western coastline to thinly populated areas (about 3 persons per square mile) in northern New Mexico and Arizona. Because at this time the primary product of most of the reserves is likely to be electricity, reasonable expectations are that preference would be given to exploration and development at sites reasonably close to population centers or transmission grids in order to minimize the costs of electrical transmissions. District heating systems would also require geothermal resources close to population centers.

A list of accidents associated with geothermal energy production is presented in Table 1. It should be remembered that there is limited experience with this source of energy, with the longest U. S. experience being approximately 15 years at the Geysers. The Larderello field in Italy, and the Wairakei field in New Zealand, in operation for 70 years and 25 years respectively, provided additional background to substantiate a number of the possible accidents.

The events which may occur would involve loss of property, hazards to life and severe detrimental impact on the environment. These occurrences are applicable to one or more types of geothermal systems, as shown in Table 65.

One major occurrence associated with the development of geothermal wells is the blowout. As with oil and gas wells, this occurs during any operation involving high pressure fluids. Depending upon the system, the blowout would result in hot fluids and steam being released to the surface or discharged through adjacent geologic structures with subsequent release to the surface being possible. An event of the first type occurred during the drilling of one of the early production wells at the Cerro Prieto field in Mexico.[91] It took days to control the well which geysered steam and salt water. It was estimated that as much as 10 acre-ft/day could flow as a result of such a blowout.

A second type of blowout occurred at the Geysers. The instability of the formation through which the well passes (an old landslide) allowed the steam to escape into the ground, with the potential of

TABLE 65 - TYPE OF ACCIDENT OCCURRENCE BY GEOTHERMAL RESOURCE

ACCIDENT	VAPOR DOMINATED HYDROTHERMAL	LIQUID DOMINATED HYDROTHERMAL	GEOPRESSURED	HOT, DRY ROCK	ALL
Exploration					
Blowouts					x
Subsidence		x	x		
Rig Accidents					x
Extraction					
Blowouts					x
Induced Seismicity and					x
Seismic Induced Failures					x
Landslides					x
Erosion					x
Rig Failure					
Production					
Fresh Water Contamination		x			
Organic Fluid Explosion or Spillage		x			
Subsidence		x	x		
Clogging and Sealing		x			

eruption, when attempts were made to cap the well. Proper grouting can minimize this occurrence. With this technique, liquid cement is pumped through a series of shallow holes several feet below the surface around the well area to create a mantel. The cemented casing is firmly surrounded, creating a shield against subsurface intrusion or eruption alongside the well.

A well blowout can cause damage to equipment, personnel, and adjacent property. The entire drill rig can be lost with the drill string operator suffering possible death or severe injury. The occurrence is manifested by the ground opening and the rig collapsing into the chasm. As a safety precaution the rig has a slide-for-life wire which allows the operator to evacuate the rig in a matter of seconds by sliding down a wire, clear of the drilling area, before the rig collapses. When natural gas is present, the possibility of fire also exists.

An earthquake could have a severe effect on a geothermal installation including rupture of pipelines and splitting of a well. Well splitting could cause contamination of aquifers supplying potable water.

A seismic event may be naturally occurring or could possible result from the reinjection of fluids during production (though this is an unexperienced and unevaluated conjecture). The disposal of water and condensate water produced in vapor-dominated fields has been handled by means of reinjection. This has been accomplished successfully at the Geysers and is being tested at Larderello. However, reinjection has never been tried in a liquid-dominated field.

A leak in a pipeline may be caused by an earthquake or by mechanical or human failure. This is generally minor, but if not repaired could lead to major failures of the pipeline. To minimize the effect of a possible seismic event, the pipelines are usually designed with loops and irregular pathways to absorb ground movement and shock.

Pressure buildup because of scaling could also cause pipelines to rupture.[89] Hydrothermal waters are often saturated with dissolved solids. As the fluid rises in the borehole the temperature decreases and the fluid becomes supersaturated. When steam is extracted at the wellhead, the volume of the water fraction decreases and the temperature drops further. At this point the dissolved solids concentration in the water exceeds the solubility and precipitation results.

Because of the precipitation of silica and other dissolved constituents, discharge canals must be cleaned periodically with a pneumatic shovel, which is dangerous and expensive. Precipitation also causes problems during reinjection because pipes clog and the permeability of the aquifer may be reduced. Treatment with slaked lime or adjustment of pH, are under study as solutions to the reinjection problem.

Geothermal operations may also cause subsidence. As with oil and gas production, excessive fluid drawoff can cause a vertically downward shift in the ground. This probably will not occur if the aquifer consists of fractured rock.[92] The only apparent ground movement for a geothermal system has been at Wairakei.[93] The affected area is greater than 65 km.[86] The region of maximum displacement is away from the fields and power stations but within 500 m of the steam mains. The movement is estimated at 40 cm/yr. The Wairakei subsidence has totaled approximately 4 m since 1956.[94] Subsidence can cause damage to buildings and equipment. Should subsidence occur in lowland coastal areas, flooding could occur. This is a particular problem for the Imperial Valley of California and for geopressured reservoirs located along the Gulf Coast.

There are additional events affecting topography which can occur as a result of construction, operation, and decommissioning of geothermal facilities.[95] These include the possibilities of:

1. Landslides and general downslope movement,
2. Sheet wash erosion, and
3. Flooding due to alteration of drainage patterns complicated by well blowout.

However, these effects have not been observed.

SECTION 9.0

OIL SHALE

9.1 RESOURCE SYSTEM OVERVIEW

Oil shales are shales which have a high organic content. This organic matter is called kerogen and is of indefinite composition, uncertain origin and usually insoluble in petroleum solvents. Kerogen is an extremely fine-grained waxy solid intimately associated with the mineral constituents of the shale. Chemical composition of kerogen in weight percent ranges from 69-80% carbon, 7-11% hydrogen, 1.25-1.5% nitrogen, 1-8% sulfur, and 9-17% oxygen. It differs chemically from crude oil in its high oxygen and nitrogen content and a higher carbon to hydrogen ratio. It can usually be recovered by thermal decomposition which begins at temperatures around 350°C (662°F). Yields as high as 150 gallons of oil per short ton of shale have occurred, but most commercial grades are between 25 and 50 gallons per ton.[96]

Interest in exploiting the U.S. deposits has existed since the first decades of the century. Interest peaked during periods of wartime crisis (1917-18, and 1941-45) when adequate petroleum supplies were considered to be in jeopardy. Oil shale was declared a leasible mineral in 1920. Shale oil was produced in the United States from eastern deposits before the Drake discovery of petroleum in 1859.

A substantial body of technology has been developed and tested on a significant scale; however, the generally low prevailing world price of petroleum has precluded commercial development of a shale-oil industry in the United States. Estonia, Manchuria, Sweden, and Scotland have operated commercial plants, and the Estonian and Manchurian industries still operate on a significant scale.

The current world price of petroleum has renewed interest in the United States in the commercial potential of oil-shale resources. In 1974, four of the six tracts offered by the Department of the Interior were leased to private interests. But even at present petroleum prices it is not yet clear that these leases will actually lead to commercial shale oil production before 1985. Nevertheless, the development and refinement of technology continues at a deliberate pace.

Thus, although the technological basis for an industry can be postulated, an industry per se does not yet exist. Therefore, an assessment of the potential for accident in the operations of an oil-shale industry must be based on conjecture and reasonable judgment.

The concentration of kerogen is measured by the Fischer assay, a standard laboratory method of thermal decomposition which measures the amount of oil produced per ton of shale. Interest in resource evaluation is focused on shales yielding 25 gallons or more per ton of oil.

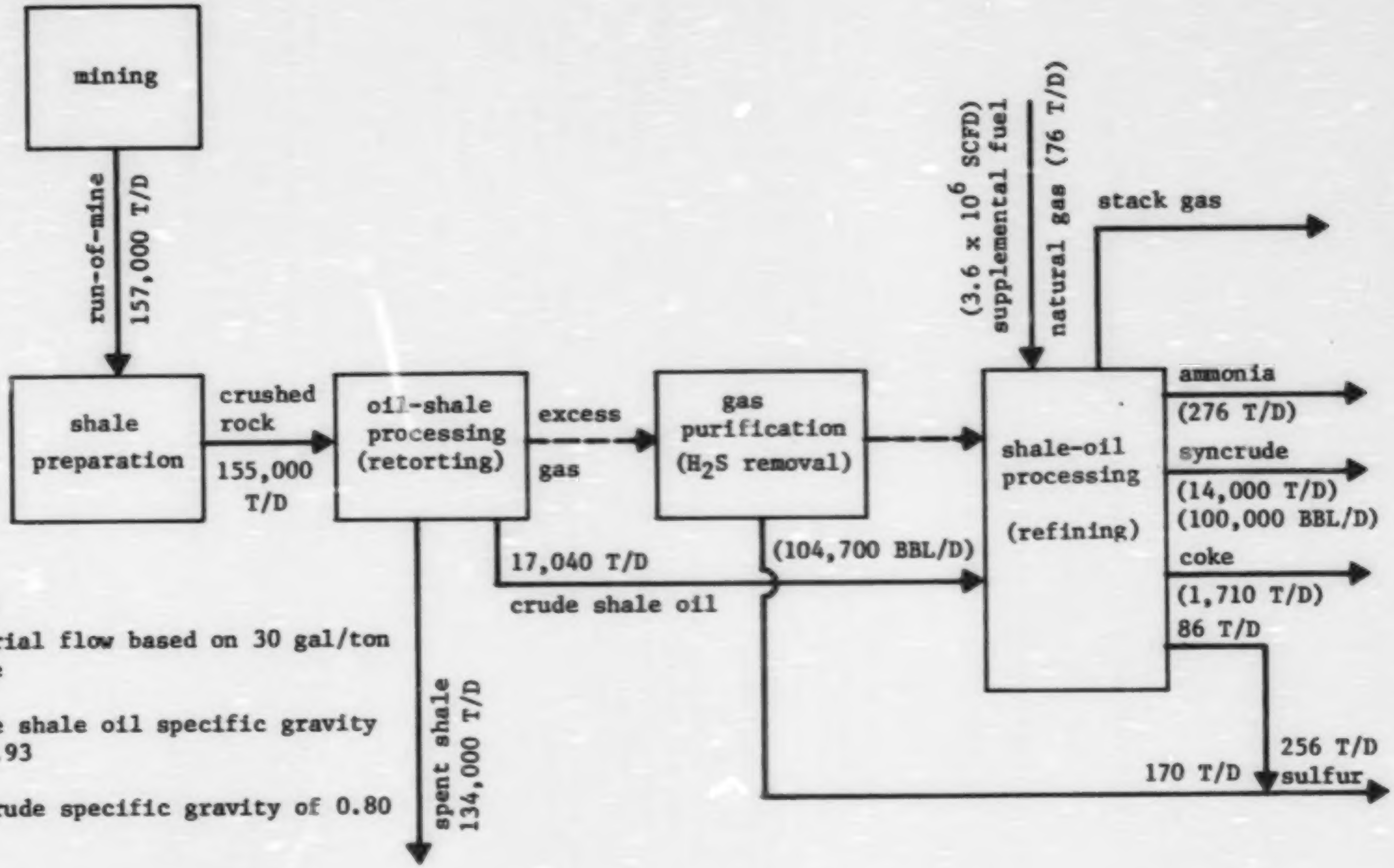
The major and predominant United States deposits of oil shale occur in the states of Colorado, Wyoming, and Utah. The deposits underlie 25,000 square miles of the three states, and about 17,000 square miles contain oil shale of potential value (i.e., assaying 25 gallons or more per ton). Of this, roughly 80% occur in Colorado, 15% in Utah, and 5% in Wyoming. Eighty percent occurs on public lands administered by the Department of the Interior. The total reserves delineated have been estimated by the United States Geological Survey at about 418 billion barrels of oil, of which 80 billion barrels are recoverable by modern mining methods.[97] Seven functions must be performed to produce from the resource a product mix of liquid-hydrocarbon fuels suited to the market now served by petroleum sources. These functions are:

1. Exploration,
2. Mining,
3. Shale Preparation,
4. Processing (Retorting),
5. Processing (Refining),
6. Product Transportation, and
7. Land Reclamation/Spent-Shale Disposal.

9.1.1 Exploration

Current technological development is based on two alternative approaches. In the conventional approach all functions after mining, are performed aboveground. In the in-situ approach, the shale preparation and retorting functions are combined with the mining function and all three performed underground. Figure 22[98] illustrates the interrelationships among the functions, and presents a schematic material flow for a postulated commercial operation producing 100,000 barrels per day of a "syncrude," i.e., an upgraded shale oil that can be accepted by a conventional petroleum refinery and pumped through a long-distance pipeline.

A system of core holes is drilled on a widely-spaced grid to estimate and delineate oil shale reserves. The grid is closer spaced if the exploration objective is formulation of a mining plan. In both cases, the cores are removed, identified as to location, and samples subject to Fischer assay for determination. The equipment used consists of surveying tools for locating the drilling positions, truck-mounted engine-powered rotary drill rigs, and a chemical laboratory for the assays.


mining
run-of-mine
157,000 T/D
shale preparation
crushed rock
155,000 T/D
oil-shale processing (retorting)
spent shale
134,000 T/D
excess gas
17,040 T/D
crude shale oil
gas purification (H_2S removal)
(104,700 BBL/D)
(3.6×10^6 SCFD)
supplemental fuel
natural gas (76 T/D)
stack gas
shale-oil processing
(refining)
ammonia
(276 T/D)
syncrude
(14,000 T/D)
(100,000 BBL/D)
coke
(1,710 T/D)
86 T/D
170 T/D
256 T/D
sulfur

NOTE

Material flow based on 30 gal/ton shale

Crude shale oil specific gravity of 0.93

Syncrude specific gravity of 0.80

Figure 22. Shale-oil production complex schematic material flow.[a]

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[a] Adapted from Reference 2

9.1.2 Mining

Several techniques can be used for mining oil shale. These are:

1. Surface, open pit,
2. Underground, shaft entry,
3. Underground, adit entry, and
4. In situ.

No experiences exist with respect to surface mining (open pit) of oil shale. The hardness of the rock indicates that such a mining operation would involve loosening the shale by drilling and blasting, and then collecting the broken shale by power shovels. Conventional drag-line removal of over burden would not be practical. Drilling and blasting also probably would be required for over-burden removal.

Extensive experience exists with the underground mining of oil shale. Since 1940, the Bureau of Mines and various private groups have cumulatively extracted more than 2 million tons of oil shale in underground mining operations. Conventional room and pillar mining techniques have been employed, with the notable feature that the rooms are unusually large in area and height because of the roof support offered by the hard shale. Room widths of 60 feet and room heights of 80 feet are practical. The freedom of movement thereby generated enables large oil-shale removal machinery to be employed. Multi-head drilling machines for charging explosives, 20 cubic yard front-end loaders, and 100 ton capacity trucks have been employed. Future development could involve automated rail haulage, or underground portable crushing equipment feeding high capacity conveyor systems.

9.1.3. Shale Preparation

The preparation needed is essentially size reduction and classification, and depends upon the process to be employed for retorting (thermally decomposing) the oil shale. The equipment used is the conventional assembly of crushers and screens. Fine grinding is not needed for the retorting processes now on the horizon. The preparation plant receives the run-of-mine oil-shale rock by truck, rail, or conveyor, and delivers sized rock to the retorting plant probably by conveyor.

9.1.4 Processing (Retorting)

Retorting processes differ in the manner in which heat is applied to reach the kerogen decomposition temperature of 800-900°F and in the manner of flow of the rock through the retorting equipment. Two processes employ gas-to-solid exchange and downward or upward flow of the prepared oil shale respectively. Another process employs solid-to-solid heat exchange in a rotating kiln. In all cases the kerogen decomposes, the oil fraction is vaporized or entrained as droplets in the effluent gases, and the oil product collected as crude shale oil. The uncondensed gases are used as fuel. The residual carbon in the spent shale can be burned for heat recovery. Electrostatic precipitators may be necessary in order to collect the fine oil droplets (mist) in the effluent gases. Multiple retorts, operating in parallel, are needed to meet capacity requirements. The operation depicted in Figure 22 could involve 12 retorting units.

9.1.5 Refining

Crude shale oil, although a hydrocarbon and a liquid, is unacceptable to a refinery because of its highly viscous waxy nature and its high nitrogen content. The first property makes it difficult to pump shale oil in pipelines and the second interferes with catalyst activity in fluid-bed cracking processing. The carbon/hydrogen ratio in shale oil is higher than for crude petroleum, and the basis for producing a crude petroleum equivalent (or syncrude) is the adjustment of this ratio, either by carbon removal or by hydrogen addition. The former approach involves an initial coking step, and the latter an initial hydrogenation step. Hydrogenation has an advantage, since the operating conditions can be selected to remove the nitrogen content of the shale oil as ammonia and incidentally remove sulfur as hydrogen sulfide.

Current interest in the refining of shale oil is focusing on the production of a syncrude that can be accepted by a conventional petroleum refinery. A specially designed shale-oil refinery is technically feasible, but its economic feasibility would seem to require large-enough volumes of shale oil and a localized market for the products.

9.1.6 Product Transportation

Since the first oil-shale operations probably will produce a syncrude, product transportation will entail pipeline transport of the syncrude to designated petroleum refining centers. The equipment for transport will comprise the storage area (tank farm) at the shale oil refinery, the pipeline and pumping stations, and the receiving tank farm at the petroleum refinery. Transport distances could reach 1,500 miles.

9.1.7 Land Reclamation/Spent Shale Disposal

Techniques used for land reclamation and spent shale disposal will depend on whether mining is open pit or underground. As already noted, no open-pit oil-shale mining operation of significance has yet been undertaken in the U.S., nor is it clear when such an operation may occur. The prospects are that an open-pit coal mine, with the exception that the equipment used would be suited to harder rock, and that the backfill operations for the pit would need to provide for disposal of spent shale before the overburden is replaced. The volumes of backfill material, whether spent shale or overburden, will be greater than the original volume disturbed during mining, so that the final ground contours after backfill will be raised from the original. Some field crushing and compacting may be needed to prepare the final surface for the backfill of the top soil, which would be available in limited quantities. In any event, the structure of the backfull volume may have a high permeability for ground water flow as compared to the original structure, even though compacting of backfill in layers is foreseen. Potential leaching of the mineral content of the backfilled material would therefore be intensified.

Less land reclamation operations would be needed in the underground mining of oil shale than for strip mining or for underground coal mining. The options for the disposal of spent shale are to fill the mined-out areas, or to establish an environmentally controlled dumping area where new land surfaces would be built. The more attractive of these two options would be determined by the site characteristics and relative locations of mining and processing facilities. In the dumping option, major efforts are required to identify suitable techniques for revegetating the new surfaces and minimizing water percolation.

For the shale oil production complex envisioned in Figure 22, production of 100,000 barrels per day (14 thousand tons per day) of syncrude requires daily disposal of 134 thousand tons of spent shale. The daily production of spent shale would cover an area of about 27 acres to a depth of one foot.

9.1.8 In-Situ Processing

In-situ processing of oil shale combines the functions of mining, shale preparation, retorting, and land reclamation/spent shale disposal as a specialized in-situ operation which produces shale oil of similar nitrogen and sulfur content but of reduced viscosity. Thus, a refining function would still be needed to produce a syncrude, although this operation could be less intense. Private activities since 1972 have focused on a large underground trial operation which currently involves an in-situ prepared volume of oil shale 250 feet high and 100 feet in square cross-section. Government activities have focused on fracturing the oil shale formation to increase its permeability to gas flow, then flowing air from one well to another through the fractured formation, igniting the shale at the air inlet well, and collecting the retorted products at the outlet well. Federal work has also involved simulating retorting of columns of oil shale of known size distribution in above-ground equipment on the scale of 150 ton batches.

As practiced currently in experimental underground work, a volume is excavated under the delineated column of oil shale to be retorted, and the excavated oil shale removed to the surface. Explosives are placed in the delineated column and detonated in a fashion designed to fracture and break down the oil shale to fill the volumes of the excavated shale plus the fractured shale with broken pieces and to produce an underground column having a predictable porosity. Retorting is begun by igniting the top surface with air and feeding the column from above with air and recycled gases. The shale is retorted, the oil collected in a sump at the bottom of the column, from which it is pumped to the surface. The recycled gases and residual carbon in the spent shale fuel the retorting operation. The process continues until a column is completely retorted, at which point is is abandoned.

The key factors affecting the attractiveness of in-situ processing are the yield of oil achieved in comparison with that for above-ground processing and the degree of use of the oil shale deposit itself. These two factors significantly affect the production costs of the oil. Achieving higher yields with in-situ processing need not be critical because a number of factors inherently favor in-situ processing. Among these are reductions in the cost of environmental compliance, the ability to retort oil-shale grades too low for aboveground processing, the potential to eliminate considerable capital cost items, and the reductions in costs by elimination in the handling of large quantity of solid materials.

9.2 ACCIDENT OVERVIEW

The estimated frequency and severity of accidents expected to be associated with oil shale resources is shown in Table 1. Because recovery of oil shale for use as a fuel source is still in the development stage, this table is based on analogy to similar technologies and reasoned judgment rather than available data.

In formulating Table 1 it was assumed that standard training and safety programs and incentive awards for mine and plant personnel will be used in a new shale-oil facility, and that the results will tend to minimize occurrence of incidents such as tripping on stairs, falling from heights, impact by falling objects too heavy for hard-hat protection, accidents with automotive equipment, and careless handling of electrical equipment. It also was assumed that underground mining on in-situ retorting operations will not lead to appreciable seismic effects because of their relatively small size and the general seismic stability of the geological structure in the three states possessing the reserves.

Only relatively minor accidents should occur frequently, that is, more than four times a year. At any one site, with competent supervision, a frequency of once per year would be unusual for many accidents for the presently contemplated production of approximately 157,000 tons/day of shale rock (Figure 22).

Roof collapse is a severe problem in the mining of coal. Roof collapse is less likely to occur in the mining of oil shale for an equivalent sized room because of the hardness of the shale. However, the rooms used for oil shale mining are likely to be larger than the rooms used for coal mining.

The potential for the occurrence of explosions within processing equipment is particularly significant in cases where high-pressure hydrogenation of crude shale-oil is the basis for the refining process. Experience with this type of operation indicates that close attention must be given by operating personnel to observing appropriate startup, on-line, and shutdown operating practices and to assure proper maintenance of the equipment. The likelihood of "gassy" atmospheres within the mine is remote. Thus gas explosions are not likely. However, explosive (combustible) dust mixtures may form.

Cameron has pointed out that health and safety should be improved in oil-shale plants and mines built to contemporary standards and in any case should not be compared to coal mining.[99] He suggests that the copper industry is more akin to oil shale.

The rationale for this approach could be in the fact that the character of the rock in oil shale and copper mining is similar, the sought after minerals in the rock are of the same level in value, and the tonnages extracted may be of a similar order of magnitude. He quotes the Bureau of Mines as stating an average annual fatality rate in the copper mining, milling, and smelting industry was 21 between 1967 and 1970. Table 66 presents fatal and non-fatal injury statistics for the metals mining industries in four western states from Bureau of Mines sources.[100]

One may expect that the mining technologies will be similar, but also that the mix of open-pit and underground mining will be different. If the mix should turn out to be significantly different, then the comparison may not be valid.

TABLE 66

METAL MINING ACCIDENTS IN SELECTED WESTERN STATES[a]

(1971 and 1972)

State	Average Men Working Daily		Days Active		Thousands of Manhours Worked		Number of Injuries			
							Fatal		Non-Fatal	
	1971	1972	1971	1972	1971	1972	1971	1972	1971	1972
Arizona	12210	12035	320	329	31243	31729	11	6	807	810
Colorado	4298	3465	260	280	8926	7690	3	5	411	314
Utah	5157	4555	307	311	12645	11361	4	3	210	110
Wyoming	1985	1915	284	290	5065	4939	3	-	112	97

[a] Reference 100

SECTION 10.0

SOLAR ENERGY

10.1 RESOURCE SYSTEM OVERVIEW

Early uses of solar energy depended on the focusing effect of materials. Solar heating was used by Joseph Priestly in 1774 to decompose HgO into mercury and oxygen. A solar distillation system, built in 1872, was used in a remote Chilean desert location to provide up to 6,000 gallons per day of fresh water to nitrate miners.[101] Also in the 1870's, a solar-heated steam boiler was demonstrated at a Paris exhibition. However, significant technological development of solar energy use did not occur until the early 1950's.[101]

This section examines the extent of the resource, the associated technology, and the accidents which occur in the solar energy resource system. Four general types of solar energy systems are included in this discussion. These are direct conversion, wind, tidal and wave, and biomass conversion.

10.1.1 Extent of the Resource

Solar energy has not as yet been used to an appreciable extent for several reasons, including a lack of technological development, little experience of potential users with solar-type systems, and a lack of sufficiently flexible and inexpensive storage capacity. This section estimates the extent to which solar energy is available in the United States. For perspective, these estimates are related, where possible, to worldwide availability and United States energy consumption.

The solar input to the earth is estimated at 5.3 x 10^{21} BTU per year.[102] The solar energy input to the United States is estimated at 1.5 x 10^{13} BTU per square mile per year. The total energy consumed in the United States in 1970 was about 6.5 x 10^{16} BTU, or roughly the energy received by 4,300 square miles in one year. Assuming a 10% efficiency for converting solar energy input to usable energy, it would have required 43,000 square miles, or approximately 1.5% of the land area of the contiguous 48 states, to provide the energy consumed in the United States in 1970. This area is about equivalent to one tenth of the area used for growing farm crops.[103] The projected growth in the consumption of all major energy resources between 1974 and the year 2000 is 9.03 x 10^{16} BTU/yr.[104] Assuming the same solar input to the United States as well as comersion efficiency, it will require approximately 60,206 square miles or 2.1% of the total land area of the 48 contiguous states to provide this energy growth. The growth in electric power consumption for the period 1974-2000 is estimated at 2.315×10^{16} BTU/yr., which represents about 25% of the gross energy consumption requirement (15,433 square miles).[104]

The use of walls and rooftops of existing buildings as solar collectors could reduce this land area requirement. A projection has been made for meeting the energy requirements of Arizona and 11 western states by 1990 using photovoltaic conversion. A 192 square mile solar cell array, coupled with pumped storage facilities could provide 14,300 MWe, which is the estimated energy need for Arizona for 1990. Similarly, to meet 40% of the electrical power needs of the 11 western states by the same year would require an array covering 2200 square miles.[105] A proposed solar-thermal power plant, covering 13,000 square miles of desert is estimated to be able to provide 1×10^6 MWe. The waste heat from this plant would be used to produce 50 billion gallons of water per day, sufficient to meet the needs of 120 million people.[106] The solar-sea resource, based upon the thermal gradients between the solar heated surface water and the colder temperature of the sea at great depths, has been estimated.[107] Existing thermal gradients in the Gulf Stream are sufficient to generate 2.08×10^7 MWe per year or 6.2×10^{17} BTU per year. This may be compared to the estimated total thermal energy requirement for the United States by 1980 of 3.20×10^6 MWe or 9.6×10^{16} BTU per year.

The generation of electricity through the use of wind power has been estimated.[9] It would require approximately 22,000 wind energy conversion systems (WECS) each with a 50 foot rotor radius, operating continuously in a 20 mile per hour wind, to generate 1% (1.6×10^7 MWhe or 5.5×10^{13} BTU) of the electrical energy used in the United States in 1971. This assumes a wind-to-electrical energy conversion efficiency of 25%. The amount of power which these same windmills could generate would represent only about 0.24% of the growth in electric power consumption between 1974 and the year 2000. It is stated by others that under certain optimum design parameters it requires 50 windmills with 50 foot rotor radii operating in a 20 mph average wind to generate 1 MWe of electrical power.[108] Compared to the previous estimate the 50 windmill configuration of optimum design would indicate a 6% conversion efficiency. A recent design of a 190 ft. rotor WECS, by the General Electric Space Division under the auspices of ERDA, is estimated to be capable of generating 1.5 MWe in a 22.5 mph windstream and 0.76 MWe in an 18 mph windstream. Compared to previous examples, this unit indicates a conversion efficiency exceeding 30%. Extrapolated estimates of available wind energy, at an elevation of 50 meters, is given as 2 MWh/M^2/year for average wind velocities of about 15.7 mph., and 3 MWh/M^2/year for 18 mph wind velocities.

The tidal power resource is estimated in terms of dissipation energy and usable energy.[102, 109, 111] The total tidal energy dis-

TABLE 67. SITE-SELECTION CRITERIA FOR TIDAL-POWERED DEVELOPMENT[a]

Country and site	Tidal range, m	Basin area, km^2	Potential annual electrical-energy production,[b] 10^6 kwh$_e$/y	Barrage length, m	L/S m/km^2	L/E, m/(10^6 kwh$_e$/y)
France:						
Lorient	4.5	16.0	97	750	47	7.7
Brest	6.4	92.0	1,130	3,640	40	3.2
Alber-Benoit	7.4	2.9	48	200	69	4.2
Alber-Vrach	7.4	1.1	18	190	173	10.6
Arguenon and Lancieux	11.4	28.0	1,090	6,275	224	5.8
La Fresnaye	11.4	12.0	470	2,760	230	5.9
Rance	11.4	22.0	860	725	33	0.8
Rotheneuf	12.0	1.1	48	330	300	6.9
Chausey	12.4	610.0	28,140	23,500	39	0.8
Somme	9.3	49.0	1,270	5,100	104	4.0
United Kingdom:						
Severn	11.5	44.0	1,750	3,500	80	2.0
United States:						
Passamaquoddy	7.5	120.0	2,025	4,270	36	2.1

[a] Reference 102.

[b] Calculated from: $E \approx (0.3 \times 10^6)\ R^2S$ kwh$_e$/yr.

sipated on earth is 3 x 10^6 MWe with the tidal energy dissipated in bays and estuaries being approximately 1 x 10^6 MWe. Usable tidal energy in the world has also been estimated at 6.4 x 10^4 MWe.[102] The efficiency of converting tidal energy to electrical energy by means of current technology, is estimated at 15%.[9]

Selection of sites for using tidal power is based upon the configuration of the location, as determined by the ratio of the barrage length (L) to the area of the basin (S), L/S, the barrage being a barrier of varying design which is placed across the mouth of a bay to form an enclosed basin. Suitability for production is determined by the ratio of the barrage length (L) to the potential annual electrical energy production (E) from the tidal basin, L/E. An optimum site would have the smallest ratios. This potential power production is expressed by $E = (0.3 \times 10^6)\ R^2S$ KWe/yr., where R is the tidal range and S is the area of the basin. The potential energy production from tidal power for several basin sites is shown in Table 67.

Wave energy dissipated on the earth is estimated to be on the order of 2.5 x 10^6 MWe or about that of tidal energy dissipation.[112] A proposed power plant design, using the horizontal movement of waves as the energy source, is estimated as having an 80% efficiency in converting mechanical energy to electrical energy. A single unit about the size of a supertanker is estimated to be able to generate approximately 50 MWe per year.[113]

It is estimated that 0.02% of the total solar energy flux of the world is available input to photosynthesis. This amounts to 4 x 10^7 MWe.[102] The energy produced is ultimately released through plant decay, used as animal forage and human food, or stored as a fuel. The electrical energy resource which can be derived through combustion of plant matter can be estimated. Assuming a best plant growth rate which may be expected, of 40 tons of dry material per acre compared with trees and grasses which are between 4 and 26 tons per acre, and a heating value of 16 x 10^6 BTU/ton (63% that of coal), the optimum heat-energy production for a single crop is 6.4 x 10^8 BTU/acre/year or 4.1 x 10^{11} BTU/mile^2/year. Assuming a 33% efficiency for the conversion from thermal to electrical energy, the required area to provide the thermal energy requirements for electrical energy in the United States for 1970 would be approximately 4.15 x 10^4 square miles or 1.4% of the total land area of the contiguous 48 states.[114] The growth in electrical power between 1974 and the year 2000 is estimated to be 6.783 x 10^{12} KWh (2.315 x 10^{16} BTU).[104] Based on the previous assumptions, the land area required to accommodate this growth is 5.65 x 10^4 square miles or 1.9% of the total land area of the contiguous 48 states.

Crop rotation may reduce the land requirement by a factor of two or three. Based upon the average solar energy incident on the earth of 1,500 BTU/ft^2, the overall efficiency of converting solar energy to electrical energy via photosynthesis is about 2.7%. This efficiency is reduced further, to about 2% of the original energy due to leaf shading, plant growth problems, combustion, steam raising, and conversion of mechanical energy to electrical power. It is estimated that worldwide energy conversion by terrestrial plants to combustible matter by photosynthesis is about ten times the present rate of energy consumption by mankind.[115]

The decomposition or digestion of algae and sewage by anaerobic bacteria is potentially a useful source of methane. A pound of dry organic material produces between 4.5 and 6.5 SCF of methane with a heat value of 10^3 BTU/SCF or 56-81% of the heating value of the original organic material.[9] It has been estimated that 100% of the United States gas needs in the year 2020 can be supplied using 5% of the United States land area with a 2% overall energy conversion efficiency, and be economically competitive with other gas producing techniques.[116]

10.1.2 Technology

The technology of the four basic types of solar energy systems, direct conversion, wind, tidal and wave, and biomass conversion, will be reviewed in terms of their operating systems and the equipment involved. The resulting end use of these systems may be electric power, hot water and space heating, absorption refrigeration, and air conditioning.

There are three methods for the direct conversions of solar energy: photovoltaic, solar-thermal, and ocean thermal energy conversion (OTEC). Photovoltaic conversion involves direct production of electrical energy resulting from the absorption of solar radiation on solid state devices, commonly referred to as solar cells. The photovoltaic system consists of three basic components: the collector, energy storage, and power conditioning. The collector is a solar cell which is constructed of semiconductor materials, generally silicon, gallium-arsenide, or germanium. The power generated by the cell depends upon its having a high light collection efficiency (low reflectivity) as well as absorption coefficients which permit the conversion to electrical energy by the interaction of the desired radiation energy with the configuration of the solid state cell materials.[9] A solar cell, 2 inches in diameter, may provide an electrical power output of 1.5 watts with a solar radiation intensity of 100 mW/cm.^{2} For operational systems, a number of cells are mounted on a common frame with a linked electrical output to form an array. Depending upon the application, a number of these modules can be linked together. An existing system which powers navigational lights on a buoy consists of 80 modules, each having five 2.17 inch diameter silicon cells, which charge 28-100 amp-hr, 12 volt storage batteries.[106]

The energy produced by any of the solar energy conversion methods may be stored until demand requires its use. Currently, the electrical energy from solar cells is usually stored by charging batteries. The electrical energy may also be transformed into other forms of energy which can be used at a later time. Some of these alternate energy storage forms include pumped hydroelectric, compressed air, flywheel, fuel cell, and superconducting magnets. The type of energy storage will depend upon the use of the electrical energy output as part of a transmission network as well as economics. The transmission of the electrical energy ultimately produced, and after power conditioning COC/AC conversion, is the same as for any of the other energy resource systems.

Solar-thermal power conversion involves focusing the radiant energy on a heat transfer medium, such as water flowing in a pipe, boiler or collector. Depending upon the system configuration and solar collector design, such a system can provide space and water heating and electricity generation. The two classes of systems discussed here are the small residential/commercial systems and the large central power and special industrial use facility.

The small systems consist of a collector, a thermal storage unit, and an end use subsystem. The collector is generally some configuration of a mirrored reflector. These can be planar with a device for focusing the radiant energy on the water pipe, or parabolic with the pipe located at its focal length. The radiant energy heats the water which then may be used to heat a building, via hot water coil heaters for example, and/or may be stored as a hot water supply. A residential solar collector would be able to heat water from 25°C to approximately 65°C. A commercial system, as shown in Figure 23, produces steam at temperatures near 750°C, this temperature being a function of the design and efficiency of the solar collector.[9] A suitably designed and sized heat-storage unit can provide a long-term, high-temperature heat energy reservoir needed to supply sufficient steam to power a steam turbine for electrical power generation. Thermal storage in small systems uses an insulated tank, with water being circulated to the collector for reheating during daylight hours.

The large facility, for central power generation or special industrial application, consists of the collector, receiver, thermal storage, and power generation subsystems (Figure 24).[9] The collector subsystem consists of a 2-axis steerable array of reflectors (mirrors) called heliostats, which track the incoming radiant energy. The array of heliostats focuses the reflected energy on the receiver, usually

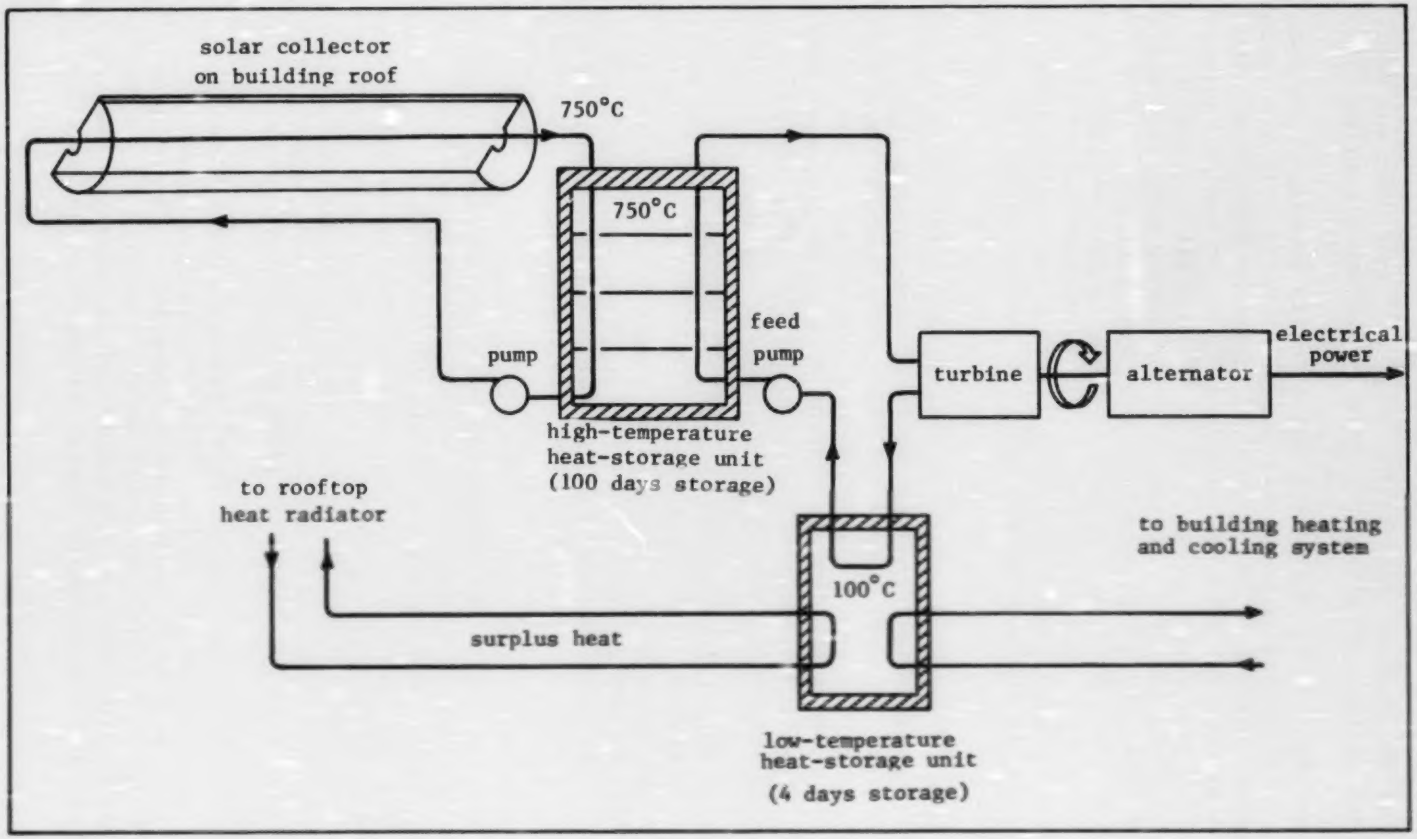
solar collector
on building roof
750°C
750°C
pump
feed
pump
high-temperature
heat-storage unit
(100 days storage)
turbine
alternator
electrical
power
to rooftop
heat radiator
surplus heat
100°C
low-temperature
heat-storage unit
(4 days storage)
to building heating
and cooling system

Figure 23. A solar-powered total-energy system for commercial installations.[a]

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[a] Reference 9

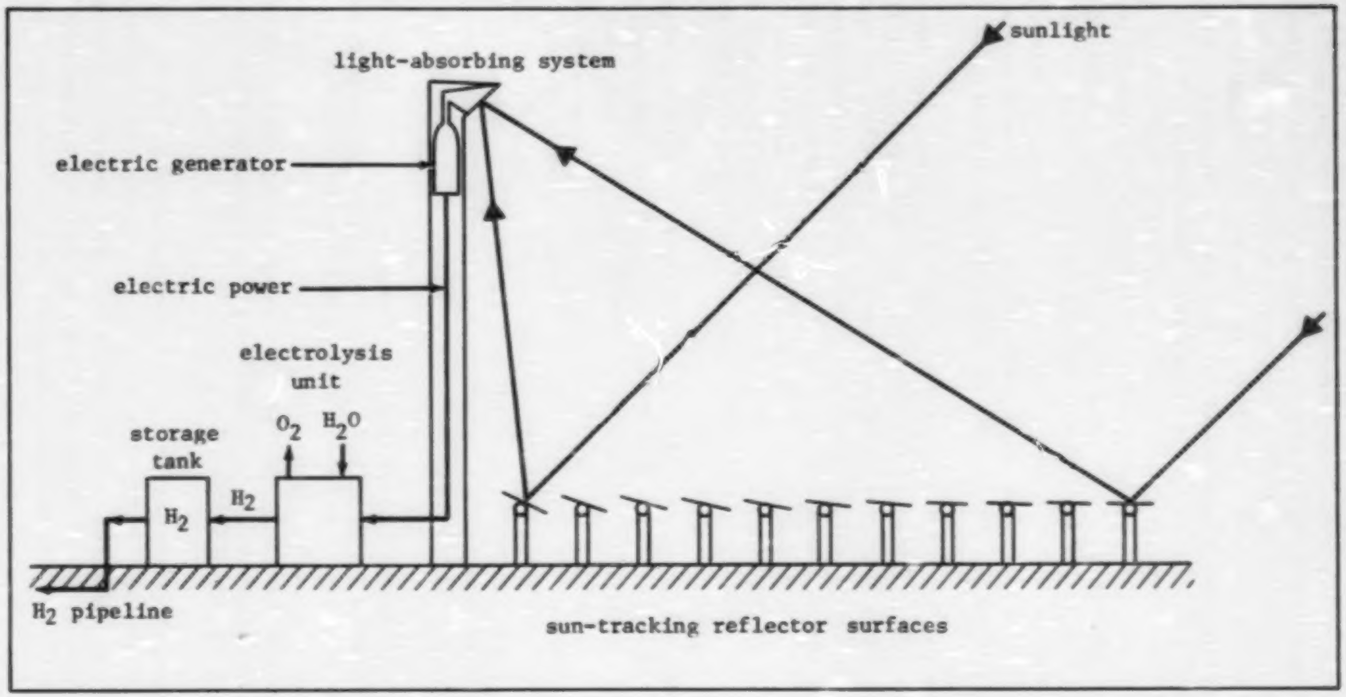
sunlight
light-absorbing system
electric generator
electric power
electrolysis unit
O_2
H_2O
storage tank
H_2
H_2
H_2 pipeline
sun-tracking reflector surfaces

Figure 24. Central station electricity generation.[a]

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[a] Reference 9

a parabolic reflector, which concentrates the energy on a boiler of small surface area. The resulting steam produced by the boiler can drive a turbine which drives a generator for production of electrical energy. Hot water from the boiler and waste steam from the turbine may be stored for future use. Storage may be in insulated tanks or one of several media whose technologies are being studied. Some of these thermal media include: Caloria HT 43, heat transfer oil; a mixture of Caloria and granite rock; Hitec, a eutectic mixture of potassium nitrate, sodium nitrate and sodium nitrite; a Caloria/Hitec combination; sodium hydroxide; and long steel ingots with longitudinal channels through whcih steam passes transferring its heat to the steel; and thermia, a hydrocarbon fluid. In addition, an electrolysis unit powered by solar-thermal energy converted to electrical energy would permit energy to be stored in the form of hydrogen.

Several special purpose industrial solar furnaces have been built and operated in Japan, France, and Russia. A 70KW furnace built in Japan in 1963 is used both for research on the properties of materials at high temperatures and to manufacture fused alumina crucibles. The furnace produces temperatures in excess of 3400°C using a 10 meter diameter parabolic concentrator. A 1-MW furnace was built in the Pyrenees at Odeillo-Fort Romeu in the 1950's and completed in 1970.[117] At its altitude of 5900 feet the sun shines approximately 180 days a year with solar intensities as high at 1000 watts/M^2. This solar energy is incident on a collector of 23,000 square feet, consisting of 63 heliostats arranged in eight tiers to track the sun, reflecting the energy to the parabolic reflector. The reflector, 135 feet high and 175 feet wide consists of 9500 mirrors having a focal length of 59 feet, concentrating the energy into a 2 foot diameter area. Sixty percent of the total thermal energy, about 600 KW, is further concentrated in a one foot diameter area at the focal point. A smaller furnace in Russia is generating 3500°C temperatures for the production of high purity refractories.[118]

Ocean thermal/energy (solar sea) conversion systems (OTEC) are based on the principle of a heat engine which uses the temperature gradient between the warm, solar-heated upper layer of water (the heat source), and the cold, deeper water (the heat sink). This type of energy conversion system consists of the water intakes, boilers, and a condenser and turbine. A schematic of a proposed modular OTEC plant is shown in Figure 25.[106, 9]

Two experimental power plants of this type were built by the French at Abidjan off the Ivory Coast in 1956, using the thermal gradient of 36°F to generate 3.5 MW each.[106] The intake pipes were eight feet in diameter to a depth of three miles, approximately three miles offshore. The boiler, condenser and turbine are the

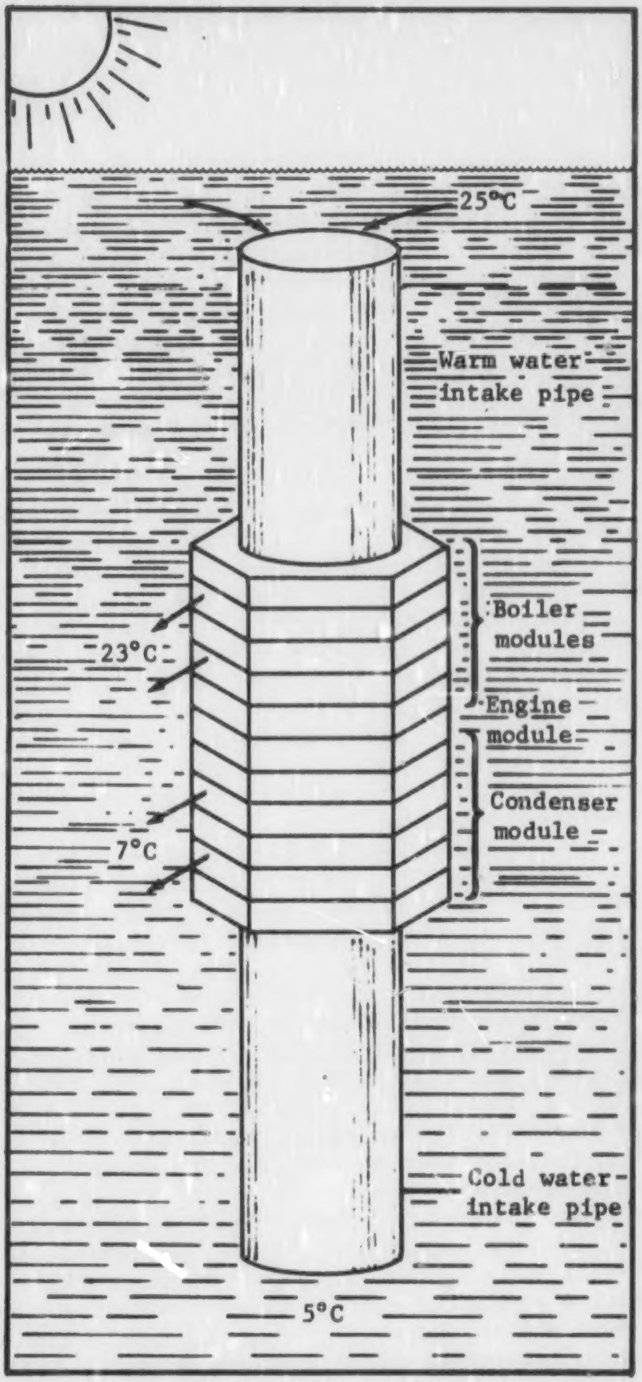
25°C
Warm water intake pipe
Boiler modules
23°C
Engine module
Condenser module
7°C
Cold water intake pipe
5°C

Figure 25. A modular solar-sea power plant.[a]

[a] Reference 106

working heart of the system. Propane, as one of the working fluids which may be used, is pumped through the boiler where the warm water vaporizes the propane at approximately 150 psi. This vapor passes through a turbine producing an energy conversion. The vapor is then condensed with the cold, deep water as the heat sink, and the cycle continues. The pumps derive power from the propane turbine. The proposed plant would be neutrally buoyant at a depth which would minimize the pressure differentials in the boiler and condenser.[119] Current ERDA estimates for such a system are on the order of $1200-1500 per KWe.[120]

A portion of the solar energy received by the earth is converted to surface winds. Windmills have used wind energy for centuries for pumping water and grinding grain. Using this energy for electric power generation, however, is a recent development. The wind energy conversion system (WECS) consists of the rotor, the conversion unit, and storage units. The conventional WECS design, a horizontal axis device, is only one configuration for extracting energy from the wind. Other designs, which may provide cost competitive operation, include the cross wind horizontal axis, the vertical axis, and the vortex rotor types. The rotation of any of these rotors drives the energy conversion equipment. The energy conversion unit may consist of an electric generator, a mechanical pump, or a direct heat pump. The choice of energy storage system will determine which conversion subsystem will be used. The electric generator energy output can be stored in batteries, in a pumped hydroelectric system, in flywheels, as hydrogen generated by an electrolysis unit, or as compressed air to be used later to drive a turbine. The mechanical pump can be used with a fluorocarbon to act as a heat pump, with air as a compressor, or to pump water for a hydroelectric configuration. The wind energy conversion system is shown in Figure 26. Several wind power plants of the horizontal axis type have been built. In 1941, the output from the 1.25 MWe Grandpa's Knob plant, near Rutland, Vermont, was connected to a utility transmission grid. This unit had two stainless steel blades, 175 feet in diameter and weighing 7.5 tons each and an electric generator mounted on a 110 foot tower, which turned to face the wind. The plant, costing $1 million, achieved full power with a wind velocity in excess of 30 mph, achievable about 70% of the time.[121] Based upon the experience of this plant, the Federal Power Commission conducted a study of wind electric power generation integrated with utility network grids. The study concluded that wind energy would be economical for plant capacities of 5-10 MW.[106] The largest foreign plant was built and operated in France from 1958 to 1960. Using a flexible 105 foot diameter, three-bladed propeller, the rated 800 KWe was reached with a wind velocity of 49 mph at 47 rpm. The plant had reached a maximum power of 1.2 MWe.[122] The National Aeronautics and Space Administration (NASA) is testing a 100 KWe wind generator at the Lewis Research Center Plum Brook facilty

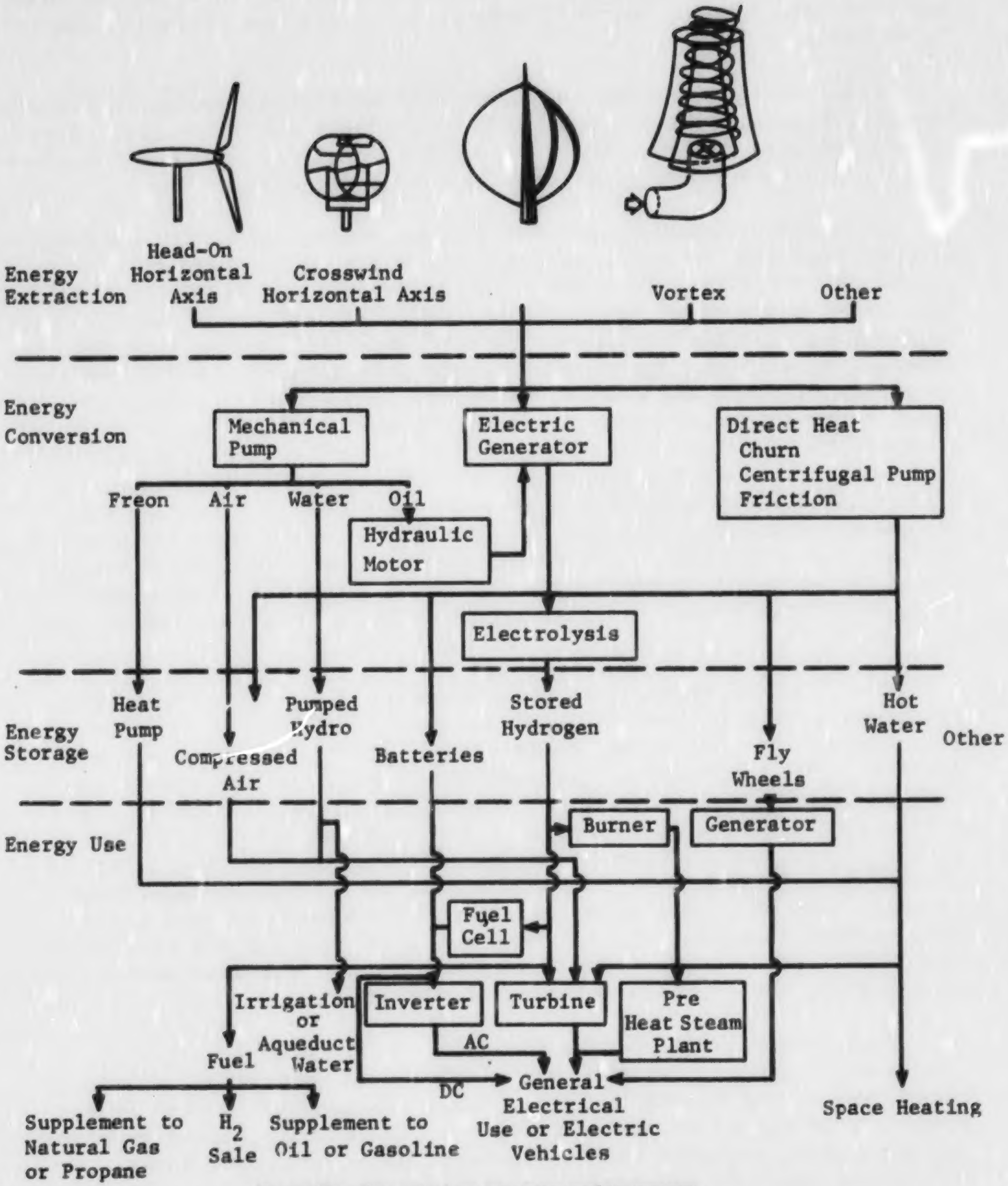
Energy Extraction
Head-On Horizontal Axis
Crosswind Horizontal Axis
Vortex
Other
Energy Conversion
Mechanical Pump
Electric Generator
Direct Heat
Churn
Centrifugal Pump
Friction
Freon
Air
Water
Oil
Hydraulic Motor
Electrolysis
Energy Storage
Heat Pump
Compressed Air
Pumped Hydro
Batteries
Stored Hydrogen
Fly Wheels
Hot Water
Other
Energy Use
Burner
Generator
Fuel Cell
Irrigation or Aqueduct Water
Inverter
Turbine
Pre Heat Steam Plant
AC
DC
Fuel
General Electrical Use or Electric Vehicles
Space Heating
Supplement to Natural Gas or Propane
H_2 Sale
Supplement to Oil or Gasoline

Figure 26. The wind energy conversion system.

at Sandusky, Ohio, in which power is expected to be achieved at 40 rpm in a wind speed of 18 mph.[123] Small residential units of 2-5 KW output which are in use, deliver their power to storage batteries for later use.

Tidal energy was used as a source of mechanical energy in France, Germany, Russia, England, and the United States until the late nineteenth century; however, the use of tidal energy as a source for electricity generation has only recently come under examination.

This resource makes use of the tidal range, the height difference between high and low tide, in conjunction with a low-head turbine to produce electricity. To place a perspective on the available head, the open ocean has a tidal range of two feet. The effects caused by water interacting with the continental shelf (shoaling), water in a bay interacting with the erection of barriers (resonance), and water interacting with the geometry of the basin (funneling), can amplify the tidal range thus enhancing the potential for available energy. As an example, the shoaling effect can produce an amplification factor of three or four times the range of the open ocean.[123] The resonance effect produces an amplification factor of almost 2.7 for the tides at the mouth of the Bay of Fundy.[124] The tidal energy conversion system consists of a barrage (the barrier transforming a bay into a basin), the sluiceways and control gates for controlling the filling and emptying of the basin, and a power house containing the turbines and generators.

The turbines used are of three major designs, bulb-type, tube-type, and straight-flow. All are designed to operate at maximum efficiency under low energy heads typical of tidal power plant conditions. The generator is designed with a rotor on the end of the turbine blades which turns in a recess in the water channel. The stator surrounds the rotor recess and is not exposed to the flowing water. There are a number of designs for barrages which will not be discussed here other than to mention that the design is determined by conditions at a particular location. The sluiceways and gates must be able to operate rapidly and reliably, opening and closing on each tidal cycle, dissipating the dynamic loads from wave action, and withstanding the corrosion effects of sea water.

There are four techniques for using tidal energy: one-way, single-basin generation; two-way, single-basin generation; multiple-basin; and pumped storage. The one-way, single-basin system is the simplest and oldest of the techniques. The basin is formed by placing a barrage, together with sluiceways, gates and power house, across the mouth of an estuary or bay. As the tide rises, the water passes through the sluiceways, filling the basin. When the level is higher than sea level, the gates are closed and the water is emptied through the turbines in the powerhouse, generating electricity. Due to the cycle of tides, the time required to fill the basin, and the time it takes to empty the basin through the turbines, this method yields 5 hours of electrical power generation and requires about 7 hours for refilling.[9] The two-way, single-basin system differs from the one-way system in that electric power is generated during water movement both in and out of the basin. In this scheme the head is lower than in the first scheme thus requiring larger and more expensive turbines. This is the technique used in the Rance tidal-power project in France. The power output from both the one-way and two-way systems are time dependent. The multiple-basin configuration consists of two, one-way, single-basin installations which are linked to provide more of a continuous output. The two basins, one at a higher level than the other, are both separated from the sea by means of barrages, sluiceways and gates, and from each other by a barrage containing a water flow path which passes through the turbine. The high level basin is filled to a level higher than the sea. Water is then released to the lower basin, generating electricity. When the low-level basin level increases to that of the high level one, its sluice gates open to the sea dropping its level. When the sea level is that of the lower-level basin, the gates are closed and the low-level basin begins to fill again, dropping the high-level basins level, at which time the cycle begins again. The period of this cycle is approximately 12.5 hours.[9] The fluctuating head in this scheme causes a power factor fluctuation of approximately 2 during a single cycle, and a factor of 5 during the lunar month. Although there is relatively continuous power output, the total energy derived from this configuration is about half that of the one-way, single-basin scheme for that basin.[124]

The pumped storage concept is a continuation of the tidal-power basin configuration, where the electrical output of the tidal power conversion is used either to pump water to a pumped storage hydroelectric power plant in a high-head scheme, or to move water to a higher basin in a low-head scheme.[126, 127] The high-head scheme permits the use of low cost turbines because they can operate at a high hydraulic efficiency. The low-head pumped storage configuration is similar to the multiple-basin system previously described.

The use of tidal power as part of an electrical power network has the major deficiency of being variable. The tidal cycles and the varying head during power generation in each of the configurations introduces a variability that is not related to energy demand. Therefore, at best, this source must be used to generate energy to be stored for use during peak demand times.

The action of wind upon the ocean surface creates waves which can be a source of power. Both the vertical and horizontal action of waves may be useful sources of energy. Present devices use the vertical motion in providing power to navigational buoys. The current simple system consists of a riser pipe, a check valve, and a turbogenerator. The vertical motion forces the water to a level above the wave height. With sufficient head, the water is drained to the sea through the turbogenerator.[128] There are proposals which would use the horizontal motion of waves for generating electricity.

Biomass energy conversion involves the absorption of solar radiation by plants, and through photosynthesis, storing the energy in the form of large molecular combustible matter, followed by a conversion of this stored energy to electrical or other energy forms. Biomass production consists of maximum use of efficient farming techniques, as well as sewage treatment operations. The farming process will not be discussed here as it is a very diversified field depending upon a number of variables such as type of crop, location, cultivation, and heat value. The system also includes the harvesting and transportation of the resources in order to make use of it efficiently. The major processes for the conversion of biomass are anaerobic digestion, combustion, acid hydrolysis and pyrolysis. Anaerobic digestion involves the action of anaerobic bacteria in decomposing algae or sewage in closed chambers. This process yields a combustible gas containing approximately 60% methane, which is then used as a fuel for electrical or heat energy production. Also produced in the digestion process is a liquid enriched in nitrates and phosphates which has application as a fertilizer.

Acid hydrolysis involves the conversion of biomass to sugar. The sugar then undergoes fermentation producing alcohols which may then be used as a fuel for heating. Pyrolysis is the high temperature destructive distillation (thermal decomposition) of the organic materials, in the absence of oxygen, yielding liquid and gaseous fuels.

The use of the various solar energy conversion techniques for the generation of electricity is shown to have variability which does not follow user demand.[114] The combination of each of the sources, their storage, and conversion to electrical energy provides an approach to electrical power generation, as shown in Figure 27.[106]

10.2 Accident Overview

Table 1 presents representative accidents and unscheduled events associated with the solar energy resources. While there has not been any large scale development of solar energy, several of the accidents listed have occurred at demonstration, pilot, and small scale plants which have been built and operated.

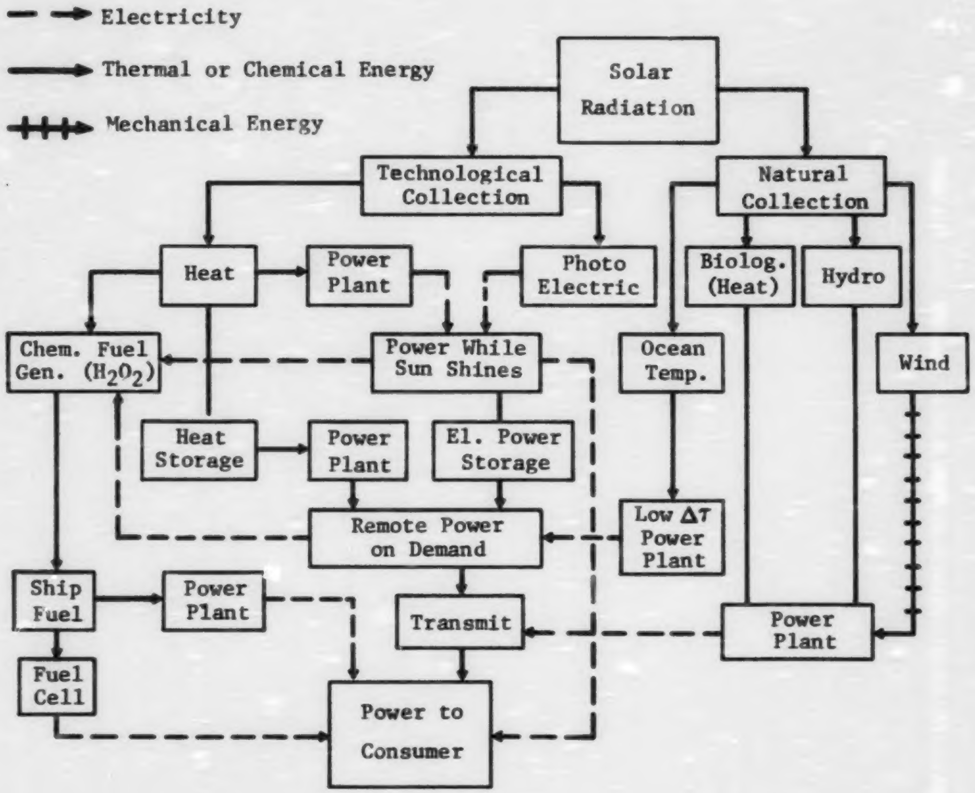
Electricity
Thermal or Chemical Energy
Mechanical Energy
Solar Radiation
Technological Collection
Natural Collection
Heat
Power Plant
Photo Electric
Biolog. (Heat)
Hydro
Chem. Fuel Gen. (H_2O_2)
Power While Sun Shines
Ocean Temp.
Wind
Heat Storage
Power Plant
El. Power Storage
Remote Power on Demand
Low ΔT Power Plant
Ship Fuel
Power Plant
Transmit
Power Plant
Fuel Cell
Power to Consumer

Figure 27. Approaches to the conversion of solar energy into electricity.[a]

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[a] Reference 106

The accidents associated with photovoltaic conversion are minor and are expected to be infrequent. Solar cell damage can be minimized with care in shielding and installation. It is anticipated that roof mounted units would be less likely to sustain damage caused by the crashing of objects into or onto the array. Injuries associated with this technology would most likely be those resulting from falls or electric shocks and burns while installing or servicing the equipment.

Solar-thermal related accidents can be major because this type of system has been used in large scale projects. These systems involve significant costs, such as for the heliostats and reflectors. As an example, the heliostats for the French solar furnace cost $21 per square foot with 23,000 square feet used. With systems being proposed to use one square mile of heliostats, the costs could be quite substantial. The cost of a tower used in a generating station as shown in Figure 24 is estimated at $15 million. Accidents involving the large scale systems may include objects crashing into the heliostats and reflector, rupture of piping seals or the boiler which carry pressurized water and steam at temperatures ranging from 150°F to 1000°F, or gross structural failure as may be caused by an earthquake.

The smaller residential size solar-thermal system would not represent significant capital costs. By the mid-1960's, Israel had over 100,000 solar water heating systems installed. Equipment failures in these systems have been shown to be so infrequent as to cause the manufacturers to increase the guarantee period from 3 to as long as 8 years.[129]

Other unscheduled events would involve injuries or unknown health effects. Glare caused by the numerous reflecting surfaces, may affect the general population in the vicinity of the plant as well as pose a possible threat to birds or other wildlife in its path. Concentrated radiation may also pose a threat to the same segments of the ecosystem. The effect of the accidental release of some proposed heat transfer fluids on the population and the surrounding environment is, at this point, uncertain. Therefore, no hazard potential for a leak or rupture of such fluids can be stated now. Occupational hazards could be expected during installation, maintenance, and operation of a plant or even the smaller residential units. Occupational injury for solar power is estimated at 0.5 - 1.6 man-days lost/MWe/yr.[130] Occupational accidents are those occurring in similar areas of other energy resources and include burns, falls, strains, and injuries due to falling objects and contact with operating equipment. Accidents involving the steam turbine or the electric generating components are those described previously in the accident report under geothermal or fossil fuel-fired power plants. Storm damage to the various solar systems may occur. The damage sustained as a result of these storms may include cell and reflector breakage, bent reflectors (home solar-thermal units), pipe ruptures, roof leaks, heliostat failure, and loss of the energy resource conversion capabiltiy.

OTEC systems are expected to have relatively minor accidents associated with them. The plant may be isolated from large populations and would not have any crew on board, except for maintenance and repair functions. There have been few such systems which have been operational. The two units off the Ivory Coast in 1956 suffered from corrosion, a problem expected to be prevalent with this type of system. The piping, 8 feet in diameter and extending 3 miles deep, became so difficult to maintain that the plant was finally abandoned. Another possible accident may involve explosion or fire involving the working fluid used, which may be propane, butane, or ammonia, or a stored energy form such as liquid hydrogen and oxygen. A large scale explosion could conceivably destroy the plant which is a sizable investment. The working fluid can also be accidentally released with no resulting fire or explosion. The effect this may have on the surrounding ocean ecosystems are not known at this time. Accidents also may occur in transporting the stored energy forms from the plant to the mainland, by ship or pipeline. The accidents associated with this are similar to those shipping accidents encountered when transporting crude oil, natural gas, and LNG.

There are several types of accidents which are associated with wind energy systems. The plants which have been built at Grandpa's Knob (1939) and in France (1958-1960) both suffered from broken blades. The blade breakage on the French unit created unbalanced forces which tore up the hub, destroying the plant. The horizontal and vertical axis turbine rotors may cause significant E-M wave interference. The extent of this event is not really known at this time, but may involve communication and navigation interference of aircraft. There can be a probability of spawning tornadoes with some designs of the vortex type. The top of the vortex column produced may pose a hazard to air navigation. There are also those accidents which may be expected with WECS. These include ice shedding from blades; blades striking people, vehicles and other objects; and wind turbulence causing damage and harm to people, structures, flora, and fauna. Design considerations and site planning may eliminate or minimize these occurrences. A major accident may occur if the tower supporting the entire unit failed causing a collapse. This might occur as a result of design error, storm, earthquake, or other external cause.

Accidents associated with tidal energy systems would include plant damage such as plant flooding, structure collapse, barrage failure or control gate failure, personnel injuries in the course of operation, maintenance and installation; and marine ship collisions or damage. Structural failure may occur as a result of storm damage, design error, or earthquake. Accidents involving the turbine and electrical generation are similar to those given for the hydroelectric plant.

Biomass conversion systems may have accidents such as explosion and fire resulting from the production of methane, in the anaerobic digestion process, or hydrogen and oxygen when power is used to dissociate water. Depending upon the cost of such facilities, design of gas handling and storage equipment, and the location of the plant relative to workers and population centers, such accidents may be major. Normal combusion techniques for converting biomass to other energy forms would sustain accidents similar to other combustion processes discussed in the coal and oil sections. As with other energy sources, occupational injuries will probably be more prevalent, although minor, and would include those accidents occurring in agricultural activities.

SECTION 11.0

END USE

11.1 ELECTRICITY GENERATION

The commercial production of electricity arose out of the development of the dynamo, the regulator, a distribution network, circuit switching and protective devices, measurement equipment (meters), and the electric light bulb. The first commercial electric generating station was located on Pearl Street in New York City. It was activated in 1882 with a power output of 792 KWe, a capacity approximate one-thousandth that of modern plants. Since that time our dependence on electricity has grown substantially to where approximately 25% of the total energy consumed today is used for electric power generation.[129,15] Projections indicate that electric power generation will account for about 40% of energy consumption in the year 2000.[129,15,9] Electricity production from all energy sources in 1974 totaled 1.86×10^{12} KWh_e while projections for 1980 and 1990 are on the order of 2.70×10^{12} KWh_e and 4.7×10^{12} KWh_e, respectively.[130] The energy sources used to produce electricity are those which were discussed previously in this report. The contribution of various sources to the production of electricity is shown in Table 68 for 1973 and 1974 with projections for 1980 and 1990.[130]

Electric power generation from fossil fuels is based upon the conversion of chemical energy to electrical energy via mechanical energy transformation. This latter transformation is based upon the principle of a conductor moving in a magnetic field inducing a current in the conductor. The basic components in the electric power generation system discussed in this section are the energy source, the power plant, the generator, and the transmission and distribution network.

11.1.1 Technology Overview

The basic types of power plant used in the generation of electricity are the boiler-fired, gas turbine, combined cycle, fuel cell, and magnetohydrodynamic. The hydroelectric power plant (including pumped storage plant), using the hydraulic turbine, was treated in Section 7.1 and will not be discussed further here. Both the fuel cell and magnetohydrodynamic type are in the developmental stages and therefore are not commercialized.

In boiler-fired plants, a solid, liquid, or gaseous fuel is burned, the heat energy being transferred to a working fluid (water and/or steam). The heat energy in the working fluid is converted to mechanical energy by a turbine and finally to electrical energy by driving a generator.

TABLE 68. ELECTRIC POWER GENERATION BY ENERGY RESOURCE[a]

RESOURCE	Contribution by Resource, $KWh_e \times 10^9$ (% of total)			
	1973	1974	1980 Proj.	1990 Proj.
Coal	846.0 (45.7)	828.4 (44.5)	1310 (48.5)	1720 (36.6)
Oil	310.7 (16.8)	298.2 (16.0)	453 (16.8)	450 (3.6)
Gas	336.0 (18.2)	320.2 (17.2)	242 (9.0)	190 (4)
Hydroelectric	271.1 (14.7)	300.3 (16.1)	292 (10.8)	319 (6.8)
Nuclear	83.3 (4.5)	112.0 (6.0)	400 (14.8)	2000 (42.5)
Other	2.3 (0.1)	2.7 (0.1)	3.5 (0.1)	21 (0.5)
Total	1849.3 (100.0)	1861.9 (99.9)	2700 (100.0)	4700 (100.0)

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[a] Reference 130

A steam power plant uses a conventional boiler and a steam turbine, and generally is equipped with cooling systems. This is the most common type of plant, accounting for approximately 78% of the U.S. generating capacity.[15] These systems transfer heat from conventional fossil fuels, nuclear, geothermal, or solar sources to water to produce high-pressure, high-temperature steam which drives a turbine. The steam is then condensed to water and recycled. To improve the efficiency of these plants various types of boiler and turbine equipment and techniques are utilized. With fossil fueled systems, additional gas cleaning devices must be used.

Gas turbine plants often are used to accommodate peak loads due to their fast start-up time, low initial cost, and short delivery time. They now represent approximately 8% of the installed generating capacity in the United States.[15] In this type of system, the gaseous or vaporized fuel is injected into a combustion chamber together with compressed incoming air, the resulting high-pressure, high-temperature exhaust being used to drive the turbine which in turn drives both the generator and the compressor. This is similar to the type of engine which is used in jet aircraft. The gas turbine, however, requires a clean gas stream, necessitating a clean burning fuel or source of high-temperature thermal energy such as a nuclear reactor.

The combined cycle power plant is a combination of these systems. In this type, the hot exhaust of the gas turbine is used to generate steam in an unfired boiler. The steam then drives a conventional steam turbine. As an example, a 1000 MW_e plant contains four gas turbines and their associated generators as well as a steam turbine with its generator. These plants are presently being used to serve intermediate system loads.

The proposed fuel cell system produces electricity from a controlled electrochemical oxidation. The three types of fuel cells are hydrogen-oxygen, hydrocarbon-oxygen, and reformer. The latter consists of a first stage reformer reacting steam with coal or hydrocarbons to produce a fuel composed of hydrogen and carbon monoxide. This mixture is then used in the fuel cell.

Since intermediate heat steps are not required, the fuel cell can theoretically approach 100% efficiency. The reactants in such a fuel cell are consumed only when the external circuit is completed, allowing the electrons to flow and the electrochemical reaction to occur. Under continuous operation, the removal of heat, water, and inert material entering the cell is necessary. The power produced is direct current (DC) and therefore must be converted before use in normal existing power systems.

Magnetohydrodynamic (MHD) power plants may be used to produce electricity in the future. This type operates at high temperature and bypasses the heat-to-mechanical energy conversion step. With a conventional generator a magnet is spun around a stationary conductor. With MHD the conductor is an electrically conductive fluid flowing through a rectangular duct immersed in a magnetic field. Three types of MHD systems are currently being investigated: open-cycle plasma, closed-cycle plasma, and the liquid metal system. The output of an MHD system is direct current (DC) generated from the induced voltage drop across the duct. Conversion from DC to AC would be required for compatibility with existing power systems.

The electrical output of the electric generating station is directed to its ultimate use by transmission and distribution networks. The transmission system consists of the lines and cables (overhead and underground), transformer, converters and switches, and controlling and metering equipment. Transmission lines have developed over the years to meet demands of usage. Currently lines carrying up to 765 KV are in service with plans for 1500 KV lines. Super-conducting power lines are being developed for AC and DC transmission. There are now approximately 40,000 miles of overhead transmission lines and 2,000 miles of underground transmission cables using about 4 million acres of land.[15]

Ultrahigh voltage (above 745 KV) transmission is currently of great interest as a means of increasing the capacity and efficiency of transmitting power. Hazards accompanying high voltage and cost and environmental problems associated with rights-of-way for overhead transmission systems have led to increased use of underground transmission. Two methods are currently being studied. One method is compressed gas insulation in which a compressed gas such as sulfur hexafluoride (SF_6) fills the pipe in which the wire is suspended thus improving heat transfer and lowering the dielectric loss. The other method involves cryogenically supercooling certain metals which causes a reduction in their resistivity, enabling smaller wires to be used for carrying more power.

A distribution system provides power at a usable level to the customer. Such a system consists of subtransmission lines (69-138kv), primary distribution lines (2.4-34.5kv), distribution transformers, secondary transmission lines (120-240v), and service lines to the customer.

11.1.2 Accident Overview

The accidents which may occur in the course of electric power generation, transmission, and distribution are shown in Table 1. Those technologies which have unique components are listed separately. Generators, transmission, and distribution systems are generally common for all energy sources and are therefore listed under a general heading.

Data on accidents associated with electrical power generation are sparse. Present Federal Power Commission (FPC) regulations require accidents to be reported to the FPC only when loss of power occurs. Thus, it is conceivable that an explosion in a boiler killing or injuring many workers will not be reported because an auxiliary boiler or generator took over and prevented a power outage. Many state regulatory agencies have reporting requirements which are more strict than those for the federal government (e.g., the New York State Public Service Commission).[131]

A serious accident which can occur at a boiler fired plant is explosion of the boiler, whether it is of conventional or fluidized bed design. Boilers operate at a combustion temperature of approximately 1500°F and pressures of 10 atmospheres.[18] Such pressures can present an explosion hazard. The probability of explosion can be increased by the high dynamic stresses caused by high temperature and erosion in localized areas where temperatures may be greater than 1500°F. Additional problems in a fluidized bed combustor are fires which can lead to explosion and interior coal dust explosions which can increase the pressure four to thirteen times.[132]

Fires and explosions may involve the fuel and fuel handling equipment. One major problem with using crude oil as a fuel is liquid and vapor leakage.[133] For example, an oil explosion and fire in the Essex generating plant in Newark killed a worker thirty feet away. In San Antonio, in 1971, an oil line ruptured spraying a hot steam line and causing a fire.[134] However, all boiler accidents may not necessarily be due directly to the fossil fuel itself. For example, a boiler exploded in western Pennsylvania because of a servomotor oil leak which caused the plant to remain down for 43 days.

Several additional but infrequent accidents can occur in the boiler fired plant. Subatmospheric pressure in the condenser could cause an implosion, destroying the condenser. A tube rupture in the boiler can occur, leading to damage to the equipment as well as shutdown. A high pressure, high temperature steam line could rupture causing injury or death to nearby workers. Statistics on these accidents were not available.

The most severe accidents which may occur at a gas turbine plant are explosion, asphyxiation, and ruptured lines. Explosion, with possible subsequent fire, can occur in the turbine, compressor, combustor, and recuperator. In gas turbine and steam plants, explosions may occur in the fluidized bed combustor system with ejection and dispersion of the bed contents. The containment vessel in an atmospheric fluidized bed system could rupture as a result of accidental pressurization whereas pressurized vessels can suffer burn-through and explode. Both atmospheric and pressurized fluidized bed systems, fired with coal, also run the risk of fire from spontaneous combustion. An additional accident which may occur in gas turbine plants is asphyxiation from toxic working fluids. Two developmental gas turbine systems, integrated low-BTU gasification and refined coal, could release toxic substances such as hydrogen sulfide, carbon monoxide, and coal tar volatiles from leaks, pressure ruptures, process failures, or human error. The fluidized-bed coal combustor could release alkali metal hydroxides through leaks, pressure ruptures, error, or spilling. In the condensor or boiler an accident could occur which would result in an alkali metal water reaction causing fire and explosion.

The experimental fuel cell system may be subject to two accidents. The first would involve a gas leak which may result in asphyxiation, fire, or explosion. For example, an oxygen leak near electrical equipment could cause a fire. The second, would be a fire caused by the failure of the heat removal system. The frequency of such accidents cannot be estimated at the present time.

As with other developmental systems, the MHD system has several potential accidents associated with its operation. These accidents include explosion and fire, asphyxiation, and magnetic explosion. If the vent or vapor handling system fails a pressure explosion may occur involving the cryogenic liquids used in the system. Any surfaces at liquid helium temperatures exposed to the atmosphere would liquefy or freeze the air. If either the liquid or solid air is contaminated with the fuel, coal dust, or hydrocarbons, the mixture can be explosive. A magnetic explosion is unique to an MHD system because it uses a large superconducting magnet providing very high flux densities. The stored magnet energy is estimated to be on the order of 570,000 BTU or approximately 280 pounds of TNT. An accidental rapid release of this energy in either mechanical or electrical form is a magnetic explosion. It can be caused through a loss of coolant or by mechanical damage.[135] The resulting explosion could injure or kill workers as well as destroy the equipment. The probability of these types of accidents occurring has not been established.

Some other accidents which may occur in the generation or electricity include power failure, flooding, electrical fires, and occupational injuries. The power failure, usually caused by an accident in the plant which knocks out the generator, causes widespread, though general damage. Customers are unable to use machinery, refrigerator and freezers, heating and air conditioning equipment, lights, etc. In addition, failure in a major generating facility may affect the network into which the power is fed causing imbalances. This in turn could cause a widespread power failure such as occured in the northeast United States in 1964. The power failure may be due to mechanical or electrical equipment failure, storms and/or flooding, or short circuiting caused by animals, birds, or humans. Major power interruption reported to the FPC due to accidents in generating stations for the years 1967-1970 are shown in Table 69.

Power outages and occupational injuries are associated with the transmission and distribution network. Line failure is a major cause of power outages. This can occur as a result of lightning strikes, falling trees, ice accumulation, storms, and vehicles striking power poles. Electrical occurrences such as short circuiting, insulation failure, and line overload and resulting fires cause power outages. A list of accidents by customer-hours lost is shown in Table 70.[136]

One of the accident types unique to overhead power transmission is the effect of corona discharge from the lines. Ozone created as a result of corona discharge can damage plants and crops. Transmission lines also could effect the operation of electrical medical devices such as cardiac pacemakers; however, data on this subject are lacking.

The occupational injuries associated with workers involved with power generation of all plant types have been tabulated.[11,137,138] The types of injuries include those affecting the back, legs, arms, face, and eyes. Causes include slipping, lifting, pulling, being struck by objects, steam burns, electrical burns and shock, and inhalation. The most prevalent injury was back strain.[138]

A study was conducted of generating plant accidents for different fuel types for 1969-1972.[137] The frequency and severity of these accidents, which occurred during 15 million manhours of work at 6 utilities, are tabulated in Table 71.[137] Accident rates expressed in terms of a 1000 MWe steam electric plant with a load factor of 0.75 are shown in Table 72.[137] The published data

TABLE 69. MAJOR POWER INTERRUPTIONS 1967 TO 1970 AS REPORTED TO FEDERAL POWER COMMISSION

YEAR	TYPE OF ACCIDENT
1968	Lost boiler fire
1968	Generator relayed out bearing vibration
1968	Water pump
1968	Boiler draft fan failed
1969	Lost control on plant gas burner
1970	Flashover on generator excitor
1970	Boiler tube rupture

TABLE 70. RANKING OF ACCIDENTS IN 1975 IN ELECTRIC UTILITIES AS REPORTED TO THE FEDERAL POWER COMMISSION[a]

Accident Group	Customer Hours Lost	Power Lost (MW_eh)
Accidental shutoff and overload includes overloading, tripping and failures of circuit breakers and relays	6,580,883	4,334
Meteorological phenomenon (not mentioned elsewhere) includes line failures due to wind, hurricane, ice, tornado, etc.	2,643,281	6,416
Vehicles or other objects striking transmission lines	2,608,018	5,889
Electrical storms	333,385	1,141
Extraneous fires (destroyed plant)	112,500	3.6[b]
Inherent faults	73,862	337[b]
Arcing	30,987	57
Explosions	27,246	__[b]
Total	12,382,916	18,177.6+

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[a] Reference 136

[b] One or more incidents not reported.

TABLE 71. OCCUPATIONAL INJURIES DUE TO ACCIDENTS IN GENERATING PLANTS[a]

Plant Type	Accident Rates							
	Frequency[d]				Severity[e]			
	1969	1970	1971	1972	1969	1970	1971	1972
Coal	3.6	5.6	11.1	10.8	121	1930	2410	1950
Oil	0	13.45	6.91	13.69	0	930	2850	461
Combination fossil	3.8	4.0	6.4	8.2	360	82	275	1540
Total, all fossil	3.6	4.7	7.5	9.1	290	605	900	1710
Hydroelectric	3.9	4.0	0.6	4.1	268	3750	79	149
Nuclear	1.3	3.4	3.1	3.0	136	84	18	43
Total, all plants	3.6	4.5	6.5	8.1	280	930	755	1430
Electric production plants[b]			6.82					
Electric utilities industry[c]			6.08					

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[a] Reference 137

[b] Edison Electric Institute data

[c] National Safety Council, 1972 Accident Facts

[d] Frequency rate is the number of disabling work injuries per 1 million employee-hours exposure

[e] Severity rate is the total days charged for work injuries per 1 million employee-hours exposure

TABLE 72. ACCIDENT RATES ASSOCIATED WITH A 1000 MWe STEAM ELECTRIC PLANT[a]

CLASSIFICATION	Annual Occupational Accident Rates Coal	 Oil	 Gas
Fatalities due to accidents (frequency rates[b])			
Power plant operation			
Published data	0.03	0.03	0.03
Philadelphia Electric Company Survey	0.10	0.013	0.007
Non-fatal injuries due to accidents (frequency rates[b])			
Power plant operation			
Published data	1.2	1.2	1.2
Philadelphia Electric Company Survey	3.3	1.2	0.7
Man-days lost to accidents, all types (severity rates[c])			
Power plant operation			
Published data	350	350	350
Philadelphia Electric Company Survey	750	130	70

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[a] Reference 137

[b] Frequency rate is the number of disabling work injuries per million employee-hours exposure

[c] Severity rate is the total days charged for work injuries per million employee-hours exposure

used is that of the National Safety Council (NSC) extrapolated by the authors. NSC figures for 1972[11] show that for the sampled electric utilities (218 units) the frequency rate for fatal and permanent total disability was 0.12 injuries per million manhours exposure. The frequency of permanent partial disability was 0.25 per million manhours, temporary total disability 6.05 per million manhours, and all disabilities 6.42 per million manhours. The utilities ranked tenth in frequency of injuries among all industries. The severity rate was 1,043 total days charged for injuries per 1 million manhours exposure. For the 3-year period, 1970-1972, the frequency for electric utilities as 6.31 per million manhours with a severity of 1,003 days charged per million manhours. These figures indicate that the frequency rate of accidents for all disabilities in the electric utility industry are below the average, but the severity is above average. Transportation accidents involving employees were higher than the overall rate[11] for all reporting truck fleets as shown in Table 73.[11] Although the overall number of occupational injuries are large, these accidents are mostly of a minor nature.

11.2 OTHER END USES

In addition to electric power generation, which represents approximately 25% of total energy consumption,[129] end uses of the various resources are transportation, industrial, residential, and commercial.

Transportation accounts for approximately 25% of the total energy consumption, which is the same as the amount used in power generation.[129,15] Of that, the automobile uses more than half (52%) with trucks using about 22%, domestic commercial aircraft more than 9%, ships and barges 4%, and railroads less than 4%. Military and government installations, automotive and aviation lubricants, and miscellaneous transportation modes account for the remainder (approximately 8%).[15,18]

The industrial sector is the largest user of energy accounting for approximately 28% of the total consumption in 1971. It was estimated that this use represented 22,623 x 10^{12} BTU's.[139] Of this energy, more than half was used in fuel burning or other thermal operations. Manufacturing used approximately 85% of the industrial energy consumed, with agriculture and mining equally dividing the remainder. The annual energy consumption for six major industries is shown in Table 74.[15] The chemicals group includes the manufacture of basic, intermediate, and end use chemicals including pharmaceuticals. It was reported that in 1972 more than 30% of the tonnage and 60% of the value of all organic chemicals were petrochemicals.[15]

Paper and allied products use was basically for heat and mechanical operations, which has been estimated at 90% and 10%, respectively.[15]

Stone, clay, glass, and concrete usage is limited to kiln heat and mechanical operations for crushing, conveying mixing, etc. The food and allied products group includes the manufacture of beverages and food as well as vegetable and animals fats and oils, prepared animal and bird feed, and manufactured ice.

TABLE 73. MOTOR TRANSPORTATION ACCIDENT RATES 1970-1972[a]

	No. of Fleets	Vehicles	Vehicle miles (000)	Accident Rate	1970-1972 Accident Rate
Public Utility - Electric	64	38,837	463,922	11.47	11.53
Trucks - all	1,866	244,745	4,742,568	9.86	10.86

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[a] Reference 11

TABLE 74. ANNUAL INDUSTRIAL ENERGY CONSUMPTION FOR VARIOUS FUEL TYPES[a,b]

Industrial Group	Fuel Type (10^{12} BTU's/year)					
	Coal and Coke	Natural Gas	Residual	Distillate	Electricity	Total Energy
Chemical	696	2,335	183	59	1,083	4,356
Primary Metals	1,706	1,095	170	77	1,018	4,138[c]
Stone, Clay, Glass, and Concrete	702	1,289	433	180	317	2,921
Paper and Allied Products	373	420	196	71	304	1,364
Food and Allied Products	177	378	65	49	261	930
Transportation Equipment	78	84	14	1	146	323
Total	3,732	5,601	1,061	437	3,129	14,032

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[a] Reference 15

[b] Petroleum refining not included. Most data are for 1970. Paper and transportation equipment data are for 1971.

[c] Includes 72 x 10^{12} BTU's of petroleum coke used in primary aluminum production.

The transportation equipment group includes the manufacture of equipment for passenger and freight transport on land, sea, and in the air. The major component in this group is the manufacture of motor vehicles (cars, trucks, tractors, buses, and trailers).

The residential and commercial sector accounts for approximately 23% of the total consumption. Both areas include energy use for space heating, water heating, cooking, clothes drying, refrigeration, air conditioning, lighting, and various appliances (e.g., television, can openers) and equipment (e.g., elevators, computers, office machines). The largest use within residential and commercial areas is space heating, followed by water heating and refrigeration. An example of the fuel consumption for the various uses are shown in Table 75.[18] For residential and commercial use the combined consumption of natural gas and distillate oil accounted for 50% of the total energy consumption for the sector.

There are many accidents associated with end use of the various energy sources. Some representative accidents for each sector are shown in Table 1.

The transportation sector has a variety of accidents which occur frequently and can be considered major. The most common accident is the vehicle collision involving one or more cars, trucks, or buses. This event becomes major when there are multiple vehicle collisions such as occur periodically on our interstate highways and turnpikes. The passenger bus accident may kill or injure a number of the passengers and may result from collision with another vehicle, a fixed object, running off the road, or collision with a train. While there are a significant number of train accidents, only about one-third are a result of regular passenger and freight operation. The remainder are involved with servicing and other operations. There has been an increase in accidents, injuries, and damage over the past several years which has been ascribed to deferred maintenance of track and equipment.[140] Data for these accidents are shown in Table 76.

Commercial aircraft accidents can be major or minor. A fire, explosion, collision, or mechanical failure which occurs during a commercial flight and which prevents the operation of flight systems can result in the loss of many lives as well as the airplane. Commercial airline fatalities reached a low of 146 in 1970 but increased to 467 in 1974.[141]

Private plane accidents, while numerous, are generally minor. However, private planes occasionally crash into occupied buildings such as schools.

Motorized farm equipment accidents involving death or injury are relatively common but generally affect only the operator. Farm vehicle accidents accounted for 3,200 deaths in 1973, for a death rate of 33.8 deaths/100,000 farm residents. There were also 110,000 disabling injuries in this group.[2]

Ship collisions can be either major or minor depending upon the nature of the accident. Accidents involving tankers are representative of many accidents

TABLE 75. ANNUAL ENERGY CONSUMPTION FOR COMMERCIAL AND RESIDENTIAL USES[a,b]

End Use	Fuel Type (10^{12} BTU's/year) Natural Gas	LPG	Distillate	Residual	Electricity	Coal	Total
Residential							
Space heating	4,375	476	2,294	NC	708	NC	7,853
Air conditioning	14	NA	NA	NA	570	NA	584
Water heating	945	85	214	NA	744	NA	1,988
Refrigeration	NC	NA	NA	NA	1,126	NA	1,126
Cooking	328	56	NA	NA	310	NA	694
Commercial							
Space heating	1,857	83	569	1,173	NC	427	4,109
Air conditioning	43	NA	NA	NA	868	NA	911
Water heating	419	18	NC	NA	263	NA	700
Refrigeration	NC	NA	NA	NA	777	NA	777
Cooking	120	5	NA	NA	26	NA	151
Total	8,099	723	3,076	1,173	5,392	427	18,893

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[a] Reference 18
[b] Data covers 1970
NA = Not applicable
NC = Not considered

TABLE 76. TRANSPORTATION ACCIDENTS

Transportation Mode	Total Accidents		Fatalities		Accident Rate[e]			
					Total		Fatalities	
	1973	1974	1973	1974	1973	1974	1973	1974
Railroad[a]								
Collisions	1,657	1,551		13	1.99[f]	1.86[f]		
Derailments	7,389	8,513		40	8.89[f]	10.22[f]		
Other	652	630		86	0.78[f]	0.76[f]		
Total (train)	9,698	10,694		139	1.0[g]	1.2[g]		
Total (all including service and non-train)	27,620	30,896		1,908	24.1[g]	27.2[g]		
Airplane[b]								
Commercial Operations	43	47	227	467	0.016	0.019	0.003	0.003
General Aviation	4,255	4,425	1,412	1,438	1.14	1.09	0.193	0.180
Motor Vehicle[c]								
Highway	16,648,100[j]		55,800	46,000			4.3	3.6
Bus (Commercial and school)	202,000		410		22.34[e]			
Boating - Recreational[d]			1,750	1,475[h]				
Farm Vehicles[c]			3,200				33.8[i]	

[a] Reference 140

[b] Reference 141

[c] Reference 2

[d] Reference 142

[e] Accident rates: Trains - accidents/million train-miles; Airplanes - accidents/million aircraft flown-miles; Buses - accidents/million vehicle-miles; Motor vehicles - accidents/100 million vehicle-miles; General Aviation - accidents/100,000 aircraft-miles

[f] Accidents/Million train miles

[g] Casualties/Million train miles; casualties include killed and injured.

[h] Estimated

[i] Deaths/100,000 farm residents

involving large ships. Tanker collisions were discussed in Section 4.0. Accidents involving pleasure craft are numerous but minor.

Table 68 indicates representative types of energy related accidents in the industrial sector. Accidents such as fire, explosion, and flooding comprise a major proportion of the accidents. Accidental release of hazardous substances also can occur.

The commercial and residential sector accidents are generally minor although almost all occur frequently. While a residential gas explosion usually is minor, major explosions can occur. For example, a gas explosion in New York City on January 13, 1967 engulfed several city blocks in fire causing extensive damage. The cause of such accidents are generally gas leaks which are ignited. These potentially are common occurrences as evidenced by the widespread usage of natural gas as shown in Table 75.

Accidents occur most frequently in the home. These accidents include falls, fires, burns, asphyxiations, electrocution, and poisoning. In 1973 there were 26,000 deaths (a rate of 12.4/100,000 persons), 4.1 million disabling injuries, and 18 million non-disabling injuries.

Most home accidents do not involve use of energy. However, accidents involving appliances, heating, and other equipment can cause injury, damage to equipment, or fire resulting in extensive damage. The damage caused by these accidents usually is small. A summary of building fire losses caused by electrical, heating, and cooking equipment is shown in Table 77. The average accident caused less than $2000 in property damage.

TABLE 77. BUILDING FIRE LOSSES CAUSED BY ELECTRICAL, HEATING, AND COOKING EQUIPMENT[a,b]

Cause	Number of Fires	Loss ($ million)
Electrical	162,600	315.8
Wiring and general equipment	101,600	203.1
Motors and power consuming appliances	61,000	112.7
Heating and Cooking Equipment	155,200	177.6
Equipment, defective or misused	89,400	116.7
Chimneys, flues overheated or defective	21,800	16.2
Hot ashes, coals	6,800	3.9
Combustibles near heaters, stoves	37,200	40.8

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[a] Reference 11

[b] Estimated for 1972

SECTION 12.0

ADVERSE NATURAL AND MAN-CAUSED INCIDENTS

This section deals primarily with events that are of such major proportions that they may have catastrophic effects. In general, these incidents "arrive with very little warning, have rapid development, and have potential for substantial destruction."[143] The natural incidents considered are hurricanes, tornadoes, floods, tsunamis, snow and ice storms, earthquakes, land subsidence, avalanches and landslides, volcanic eruptions and meteorite impact. Also covered are anthropogenic unscheduled incidents: airplane and missile crashes, sabotage, terrorism, and war activities.

An overview of the severity and frequency of each of these is given in Table 1. An in-depth study of each of these is clearly beyond the scope of this paper. The purpose here is rather one of collection of summary information, and the presentation of a broad overview of the vulnerability of the non-nuclear energy systems. Precise cost figures of damage to energy facilities as a result of these incidents were difficult to determine and are generally not included.

All industrial installations are potentially vulnerable to disasters. In general, their vulnerability is dependent upon their geographic location, their physical characteristics, and their dependence on other industrial entities for supply materials, transportation, and other resources. Often the magnitude of the vulnerability can be reduced by proper management and proper contingency planning.

Emphasis is placed on the vulnerability of petroleum and the natural gas industries since together they supply 75-80% of the total energy requirements of the nation.

12.1 NATURAL DISASTERS

The effect of a natural disaster on an industrial installation can often be so severe and damaging that it can be compared to the effect of a nuclear blast whose point of detonation is a few miles from the plant. In particular, the high wind velocities and low pressures associated with tornadoes, and the extreme heat generated by a major fire are quite similar to the condition following a nuclear explosion. The loss of life and economic damage can be catastrophic. Up to 26 natural disaster areas are declared in a single year. Natural disasters cause about 500 to 600 fatalities each year and economic losses average 10 to 15 billion dollars.[144]

The types of damage produced by natural disasters include flood damage to storage facilities, processing facilities, and transmission lines, physical stress damage to processing facilities, rupturing of pipelines, and explosions and fires resulting from escaped gases and highly flammable liquids.

Natural disasters are often concentrated in specific geographic locations. Unfortunately, these generally coincide with the concentration of energy industries. These issues and others are elaborated below for each type of natural disaster.

12.1.1 Hurricanes

Hurricanes or tropical cyclones develop over ocean areas in latitude 8° to 15°N, then generally follow a north-easterly course approximating the Eastern coastline. The counterclockwise winds associated with hurricanes may exceed 200 miles per hour. Winds in excess of 100 miles an hour are common in the storm's path. Hurricanes are accompanied by torrential rainfall, resulting nearly always in serious flooding.

On the average, eight hurricanes develop during a year, of which four affect some part of the United States. Of these, approximately one each year is of devastating proportions, with more than 50 lives lost, and economic damage amounting to billions of dollars. Hurricane Betsy in 1965 caused close to five billion dollars damage. It is estimated that losses from hurricane Agnes in 1972 exceeded that figure. During the years 1951 through 1965, the total loss of life due to hurricanes was 5,475, or an average of 110 per year. Total economic damage (in unadjusted dollars) was over 4 billion dollars, for an average of 87.6 million per year.[144]

Hurricanes generally develop in or near the Caribbean Sea or the Gulf of Mexico. They then move north and east, generally hugging the coastline, until finally dissipating over land, or heading out into the Atlantic. Hurricanes have been known to travel as far north as Maine; however, the states most affected are Texas, Louisiana, Florida, Alabama, Georgia, and North and South Carolina. This same area contains a large concentration of oil refineries and natural gas installations. By 1971 figures, 5,032,600 barrels of crude oil per stream day, or 38% of the national total, were processed in refineries located in this region.[144] For natural gas, 16,633,870 million cubic feet, or 74% of the total national natural gas supply came from this region.[145]

Coal production areas are not greatly threatened by hurricanes. Approximately 5% of the national production total is mined in the hurricane risk area.

According to sources at the National Hurricane Center, the past summer (1976) was something of an anomaly with regard to storm paths which affect the United States. The whole hurricane pattern appears to have shifted towards the east and south. No storms developed in the Gulf of Mexico or in the Caribbean. (This is only the second time in this century that this was the case). Several of the Atlantic storms which did develop, recurved much further south than usual. Similarly, there were an unusually large number (four) of major Eastern Pacific storms which affected the land areas of Mexico and some parts of California instead of remaining out in the Pacific. This unusual pattern appears to be related to the high atmosphere wind circulation patterns which affect the Northern Hemisphere, and which seem to have shifted. There is, however, no evidence to indicate that this shift is permanent, and that next year's pattern will be similar. Estimates of risk to facilities must be based on the long-term histories of natural events, not on the anomalies of a given year.[146]

The damage caused by hurricanes is due to flooding and to the high wind velocities which may carry a great deal of debris. Low-lying storage facilities and processing facilities are vulnerable to floods. Flooding may also break communication and power lines, and disrupt aboveground transportation facilities. This may result in a serious disruption of necessary supplies. Offshore drilling platforms are particularly vulnerable. The Council on Environmental Quality (CEQ) has studied the development of petroleum reserves located in the Outer Continental Shelf (OCS) in the Atlantic and off the coast of Alaska. CEQ has calculated the probability of one or more storms exceeding the 100 year and 200 year design storm (the worst storm expected in 100 or 200 years) and the corresponding impact on offshore facilities. These figures are shown in Table 78. These figures all assume a field life of 20 years. Doubling the assumed field life results in a doubling of all the estimates. The table clearly shows that though there is potential for damage to the well platform, the storage facilities, and the tanker moorings, the probability of a well blowout is low.

12.1.2 Tornadoes

Tornadoes are small, intense cyclones in which air spins at high speeds. Tornadoes appear as funnels, containing condensed moisture, dust, and debris. Wind speeds in a tornado exceed those in any other kind of storm. They are estimated to be between 200 and 250 miles per hour.[147]

Tornadoes occur much more frequently than hurricanes, but they are more short-lived (less than a day) and impact a relatively small area. Because of their intensity and narrow limits of their paths, they take a heavier toll of lives per year than hurricanes, but result in less economic damage. Approximately 10,000 people lost their lives in tornadoes during the years 1916 through 1970, an average of 194 per year. Property loss was estimated to exceed $40 million per year.[144]

Most tornadoes occur in the midwest. Oklahoma has the highest rate of occurrence, approximately 300 per year. At least 200 per year occur in northern Texas and eastern Kansas. The remainder of the midwest, as far north as Iowa and as far east as western Ohio, has at least 100 per year. The northern halves of Mississippi and Alabama also report at least 100 per year. The incidence in the remainder of the country is insignificant.[147]

Out of a total national crude oil processing capability of 13,284,985 barrels per stream day in 1971, 3.6% are processed in plants located in Oklahoma, 3.0% in Kansas, less than 0.1% in Nebraska, 6.6% in Illinois, 4.7% in Indiana, and 0.1% in Missouri.[144] Thus, approximately 18% of crude processing capacity is located in areas where the incidence of tornadoes is greater than 100 per year.

TABLE 78
ESTIMATE OF EFFECT OF STORMS EXCEEDING PREDICTED 100 AND 200 YEAR STORM LEVELS

			PROBABILITY OF DAMAGE OR DESTRUCTION OF		
	PROBABILITY OF PLATFORM COLLAPSE	PROBABILITY OF WELL BLOWOUT	FLOATING STORAGE	UNDERWATER STORAGE	TANKERS SINGLE POINT MOOR
100 Year Storm					
design margin of safety = 1.5	9%	0.36%	9.5%	9.5%	
design margin of safety = 2.0	4%	0.16%	4.4%	4.4%	4.4%
200 Year Storm					
design margin of safety = 1.5	5%	0.2%	4.7%	4.7%	
design margin of safety = 2.0	2%	0.08%	2.2%	2.2%	2.2%

Of a total national production of 22,53,698 million ft^3 of natural gas in 1972, 8.0% came from Oklahoma, 3.9% from Kansas, and negligible amounts from Nebraska, Illinois, Indiana, and Missouri. Approximately 12% of the natural gas production is therefore located in areas where the incidence of tornadoes is greater than 100 per year.[145] The production capacity for petroleum and natural gas located in Texas is not included here since these wells are generally on the coastline where the incidence of tornadoes is low.

Coal production is not threatened to any significant degree by tornadoes. Only 2% of the total national production capacity, or 11,660 short tons, is mined in areas of high tornado incidence.

The extremely powerful wind-forces associated with tornadoes are their primary danger. Small pieces of debris which are carried up acquire piercing strengths of projectiles. The effect is similar to the destruction caused by explosives. Another danger is the extreme low atmospheric pressure in the center of the tornadoes. Air at normal pressures within a building enclosed by a tornado can blow out the walls because of the pressure differential. The most vulnerable aspect of any installation is the actual physical plant and its fittings. Aboveground communication and power lines are also vulnerable.

12.1.3 Floods

Floods occur as a result of a variety of atmospheric and/or environmental conditions. Among these are rainstorms, hurricanes, tidal waves, snowmelt, and dam failure. The geology and vegetation of a region significantly influence the severity of a flood. If the soil surface is porous, excessive water can quickly drain out. If it is composed of clay, drainage is poor, and much debris consisting of mud and silt is produced. An area which is heavily wooded or containing grasslands will entrap considerable precipitation on leaf surfaces, and thereby reduce flood potential.[148]

The total damage caused by flooding in 1966 in the continental United States was approximately 1.7 billion dollars. In spite of various flood control measures, the predicted damage in 1980 is 2.4 billion dollars.[148] The loss of life associated with floods in the United States is not great, however, averaging less than 50 per year.[149]

The areas most prone to flooding are the Northern Midwest states, particularly the Upper Mississippi, Missouri, and Arkansas River valleys. Next, with about half the incidence rate of the Northern Midwest, are the northern parts of both coastlines, and the states south of the Great Lakes region, particularly Indiana and Ohio. Less than 10% of the total national capacity of oil production and gas production is based in these areas.[144,145] The flood hazard to coal mining appears to be minimal.

Low-lying storage and processing facilities are vulnerable to floods; however, the most vulnerable components of energy systems is aboveground transportation facilities, such as bridges, railroads, and roadways.

12.1.4 Tsunamis

Tsunamis or seismic sea waves are generated by sudden displacement of earth under water, as during an earthquake. They are also, but infrequently, caused by underground landslides. Though potentially very destructive (the Krakataw volcanic eruption in 1883 caused a tsunami over 90 feet high, which rolled over Java and Sumatra, and killed about 30,000 people), they are quite rare. Since 1900, only seven major tsunamis with wave heights of 15 feet or above have been reported in the world. However, the most recent, in 1964, hit Crescent City, California, and resulted in 119 deaths and $104 million of damage. In a risk assessment study for a liquified natural gas terminal (LNG) in Oxnard, California, it was estimated that a tsunami of over 20 feet has the probability of occurring once in a hundred years.[7]

The study further states that should a tsunami occur, it would result in some minor flooding of the LNG facility, but the force of the water would not be sufficient to cause damage. However, LNG tankers would have to leave the dock area, and the ship-to-shore transfer system would need to be drained. Sufficient warning usually is available in the United States for tankers to leave fixed berths. No large scale damage or LNG spills are anticipated as a result of tsunamis. The previously cited CEQ study, summarized in Table 79,[150] does show, however, that tsunamis could seriously threaten underground storage facilities and tankers moored at fixed berths.

12.1.5 Snow and Ice Storms

Snow and ice storms are familiar and frequent phenomena in the northern parts of this country. The loss of life resulting from winter storms is often high. A United Nations study stated that 1,620 lives were lost in the United States during the period 1947-1970. This compares with 1,890 due to tornadoes, 1,730 due to hurricanes, and 680 due to floods for the same period.

Though economic damage can be large, the major economic loss is generally loss of livestock and loss of farm produce.[147] Substantial industrial installations are not seriously threatened by winter storms, except in the disruption of transportation facilities and overhead electric power and communication lines. Overhead lines are particularly susceptible. It has been reported that during a winter storm in 1960, ice deposits of over eight inches in diameter built up on some electric power lines, with a loading of twelve pounds per foot causing many lines to fail.[12] In general, however, damages resulting from winter storms are repaired in a matter of days. Winter storms are not considered a major hazard to energy production facilities.

12.1.6 Earthquakes

Earthquakes are movements of ground surface. The initial motion which occurs to relieve a point of stress produces shock waves which radiate out from the center (epicenter). This motion is generally related to a fault, which is a line along which earth moves in different directions; e.g., up on one side and down on the other, or in opposite horizontal directions. Earthquakes are measured on an intensity scale, the Richter Scale, or the modified Mercalli scale. The Richter Scale is a logarithmic scale, i.e., a value of

TABLE 79 SUMMARY OF THE EFFECT OF NATURAL PHENOMENA ON VARIOUS ELEMENTS OF THE OIL PRODUCTION SYSTEM[a]

ELEMENT		SEVERE STORM	EARTHQUAKE		TSUNAMI	VOLUME OF OIL AT RISK PER EVENT
			VIBRATION	SOIL STABILITY		
Platform		Slight[b]	Slight[c]	Slight[d]	None	500 to 1500 bbls/well/day
Pipeline		None	None	Serious[e]	None	10,000 bbls or more
Storage	Ashore	Slight[f]	Slight[g]	Slight[d]	None	Up to 1,000,000 bbls or greater[h]
	Afloat	Moderate	None	Slight[i]	None[j]	200,000 to 1,000,000 bbls
	Underwater	Moderate	Serious	Serious	Serious	100,000 bbls or greater
Tankers Underway		Slight[k]	None	None	None	
Tankers Moored at single point moors		Slight[l]	None	Slight[l]	None[l]	500,000 to 2,000,000 bbls
Tankers at Fixed Berth		Slight	None	None	Serious	

[a] Reference 150

[b] Storm forces in both areas are comparable to those in the North Sea.

[c] Provided earthquake resistant design features are used.

[d] Provided careful soil analysis program is followed.

[e] It may be possible to reduce threat by line routing over less susceptible areas.

[f] Provided tanks are sited away from flood prone areas.

[g] Provided free surface effect is reduced.

[h] Dikes give protection against damaging oil spill.

[i] Assumes control can be regained before floating storage grounds or capsizes.

[j] Provided floating storage is moored in deep water.

[k] Assumes regular inspections and prudent seamanship.

[l] Assumes ship control is regained before grounding.

one increase in the number (for example, from 4 to 5) means that the intensity of the quake is higher by a factor of 10. Quakes of intensity 4 or less cause minor damage. At an intensity of 4.5, local damage is caused. Intensity 7 indicates a major earthquake which can be recorded over the entire earth. On the average, 14 earthquakes of intensity 7 or greater occur during the year throughout the world. The maximum intensity reported was 8.6. A quake of this magnitude releases tremendous amounts of energy (for comparison, the Hiroshima atom bomb would have rated 5.7 on the Richter Scale), and results in serious damage or destruction of practically all constructed edifices. Earthquakes also produce secondary effects such as tsumanis, avalanches, and landslides.[148]

Major earthquakes are potentially highly destructive. Throughout the world, on the average, 10,000 die each year from earthquakes, with damage amounting to $400 million dollars. Two major recent earthquakes in the United States illustrate their potential for causing damage. The Alaskan Good Friday Earthquake of 1964 measured between 8.0 and 8.6 on the Richter Scale, making it one of the most severe recorded. Three hundred people (out of a total Alaskan population of 250,000) were killed. Property damage was estimated at $210 million dollars. Industry and civil life were completely disrupted with the destruction of harbors, docks, railroad tracks, bridges, highways, power facilities, and structures of many kinds. Had the earthquake occurred in a more populated part of the country, the loss of lives and damage would have been many times greater. The San Fernando (California) earthquake in 1971 measured 6.6 on the Richter Scale, which is considered "moderate" rather than "severe". Nevertheless, 65 lives were lost, and damage has been estimated at $500 million dollars.[148] It has been estimated that if an earthquake as severe as the 1906 San Francisco quake (estimated intensity of 8.25) were to hit the area, the damage would be on the order of $20 billion.[147]

The entire western part of the United States exhibits great seismic activity. Areas of major seismic risk (frequent quakes with some damage) include essentially all of California, and most of Nevada, Utah, Idaho, and Montana. There are also pockets of major seismic activity centered around Puget Sound, southwest Kentucky, southern Illinois, southeastern Missouri, the South Carolina coastline, along the St. Lawrence Seaway, and in Alaska. Moderate seismic activity may be found in the remainder of the West, around Kentucky, Tennessee, and Indiana, around the Appalachian mountains, and in most of New England and northern New York. The southern coastline, including Texas, Louisiana, and Florida, is the only section of the country which seems to be relatively free of seismic risk.

Approximately 18% of our total crude oil refining capability is located in regions of major seismic risk, with another 14% located in moderate risk regions.[144] The total natural gas supply is little affected. Only 3% is located in the area of major risk, and an additional 5% in the area of moderate risk.[145]

The most vulnerable part of the oil and gas industry are the pipelines. Several major pipelines are located in California. Some cross major faults more than 20 times.[7] Similarly, some of the major pipelines from the oil and gas fields in Louisiana and Texas cross the significant risk region of the Kentucky, Missouri, Illinois area.[145] The newly constructed Alaska pipeline crosses over four major active faults.[148] The coal mining industry is also vulnerable to earthquakes. Approximately 15% of the total national coal production is located in earthquake-prone areas. The primary hazard from earthquakes in coal mining is roof and sidewall collapse.

All parts of energy industry installations are potentially vulnerable to earthquakes. The sudden collapse of part of a structure in which oil or gas is housed or processed will often result in serious fires. Transmission pipelines can be sheared by seismic movement. Landslides, caused by earthquakes, can severely damage storage tanks and processing machinery. Especially vulnerable are storage tanks which are built on inclines which can be carried along by powerful landslides.

The CEQ Outer Continental Shelf oil and gas study can again be used as an example of potential impact. The CEQ estimates for damage to offshore facilities due to earthquakes are given in Table 80. The figures given assume a field age of 20 years. Doubling the field age causes a doubling of the estimated failure probabilities.[43]

Table 79, giving the summary of the effects of natural phenomena on the oil production system, shows that earthquakes are considered a serious threat to underwater storage tanks.

Although probability estimates for failure of hydroelectric dams per se are not available, a study of the probability of failure of 13 dams in California has been performed.[a] Probability estimates are presented in Table 81. Estimated fatalities and damages are present in Table 82. These fatality and damage estimates are based on the assumption of total and instantaneous failure of dams filled to capacity.

12.1.7 Land Subsidence

Subsidence can be defined as any displacement of a generally level ground arising from surface or subsurface causes.[148] Earthquakes often cause land subsidence. Other causes are the uncontrolled pumping of water or oil from underground. This is a known problem in the development of oil fields and is discussed elsewhere. Land subsidence (other than that associated with earthquakes) is not generally considered to be a major hazard to the energy industries.

12.1.8 Avalanches and Landslides

With the possible exception of a few oil and gas pipelines, no large industrial installations are located in the path of snow avalanches. These pose no significant danger to the oil and gas industry. Some coal mines may be threatened by avalanche activity. Data on economic losses due to avalanches are not readily available.

Landslides occur on slopes consisting of a variety of geological materials and develop through a variety of mechanisms and causes. Lanslides are often initiated by earthquakes. Landslides can also be brought about by

TABLE 80 ESTIMATES OF OFFSHORE DRILLING FACILITIES DAMAGE DUE TO EARTHQUAKES[a]
(FIGURES ASSUME A DESIGN SAFETY FACTOR OF 2.0)

MAGNITUDE OF QUAKE (RICHTER SCALE) STRUCTURE IS DESIGNED TO WITHSTAND	LOCATION OF STRUCTURE	AVERAGE NUMBER OF TIMES QUAKE EXCEEDING GIVEN MAGNITUDE WILL CAUSE PLATFORM COLLAPSE	AVERAGE NUMBER OF TIMES QUAKE EXCEEDING GIVEN MAGNITUDE WILL CAUSE WELL BLOW OUT	AVERAGE NUMBER OF TIMES AN UNDERWATER STORAGE TANK WILL BE DESTROYED
6.6	Atlantic (seismic hazard is low to moderate)	0.23	0.009	0.23
7.2	Atlantic	0.09	0.0036	0.09
	Gulf of Alaska (seismic hazard is serious)	2.8	0.11	2.8
8.6 (most severe earthquake recorded)	Gulf of Alaska	0.28	0.011	(no estimate given)

[a] Reference 150

TABLE 81 PREDICTION OF EARTHQUAKE IN CALIFRONIA BY FAULT THEORY USING A COMPUTER[a]

Name of Dam	Estimated Probability of MM VIII per Year[b]	Estimated Probability of MM IX per year[c]	Estimated Probability of MM X per year[d]
St. Francis	NC	NC	NC
Van Norman	0.014	0.0049	0.00003
San Andreas	0.044	0.014	0.003
Lower Crystal Springs	NC	NC	NC
Stone Canyon	0.012	0.0014	0.0003
Encino	0.012	0.0013	0.0002
San Pablo	0.076	0.032	0.011
Folsom	NC	NC	NC
Shasta	NC	NC	NC
Chatsworth	0.013	0.0028	0.00003
Mulholland	NC	NC	NC
Upper San Leandro	0.12	0.063	0.023
Lake Chabot	0.12	0.057	0.021

a Reference 150

b Significant Probability of Failure

c Substantial Probability of Failure

d High Probability of Failure

NC = Not Calculated

TABLE 82 ESTIMATED EFFECTS OF TOTAL AND INSTANTANEOUS FAILURE OF DAM FILLED TO CAPACITY[a]

NAME OF DAM	FATALITIES		DAMAGE ASSESSED IN U.S. DOLLARS
	DAY	NIGHT	
St. Francis	- Not calculated -		
Van Norman	72,000	123,000	3×10^8
San Andreas	21,000	33,000	1.1×10^8
Lower Crystal Springs			
Stone Canyon	125,000	207,000	5.3×10^8
Encino	11,000	18,000	5×10^7
San Pablo	24,000	36,000	7.7×10^7
Folsom	260,000	260,000	6.7×10^8
Chatsworth	14,000	22,000	6×10^7
Mulholland	180,000	180,000	7.2×10^8
Upper San Leandro	36,000	55,000	1.5×10^8
Lake Chabot			
Shasta	34,000	34,000	1.4×10^8

a Reference 150.

b No allowance for evacuation.

improper disposal of mining debris. The debris (called "tailings") is dumped to form an artificial hill, which is loosened by rainfall and wind resulting in a landslide. One such landslide in Aberfan, Wales, in 1966, engulfed a portion of the town. One hundred forty-four people lost their lives. In general, landslides are not considered a major hazard to energy industry installations.

12.1.9 Volcanoes

There are no currently active volcanoes in the continental United States. Although mountains making up the Cascade Range of Washington, Oregon, and California are volcanic, and there are active volcanoes in both Alaska (Mt. Katmai) and Hawaii, (Mauna Loa, Kilauea), none appear to pose a significant threat to energy systems.

12.1.10 Meteorites

Approximately 3500 meteorites strike the earth each year. Most of these are very small, weighing under 10 pounds. On the average, one meteor weighing as much as a ton impacts the U.S. in a given year. The probability of a meteor hitting a major industrial installation (in this case an LNG facility) has been calculated to be 6.07 x 10^{-9}, of which 5% would penetrate storage tanks.[7] It may be concluded that meteorites present no significant danger to energy installations.

12.2 Adverse Man-Caused Incidents

The destruction potential of man-caused adverse incidents is very great. For example, a well-planned act of sabotage or a nuclear weapon can completely demolish all structures within an area. Other man-caused events may produce minor immediate damage, but their cumulative effect may be significant (e.g., industrial sabotage). Two types of man-caused destructive incidents are discussed: those which are unintentional (airplane and missile crashes), and those which are planned and executed with the intent to harm and destroy (sabotage, terrorism, and war).

12.2.1 Airplane and Missile Crashes

The commercial air carrier fleet consists of approximately 2500 aircraft. These generally have an excellent safety record. The number of major accidents in which more than 100 people are killed are less than 1 per year. The total number of accidents of all kinds average 30 per year. The figures for general aviation aircraft is approximately 180,000. These average approximately 3800 accidents per year of which approximately 50% occur within 5 miles of an airport. These accidents are generally minor in terms of loss of lives and economic loss. If a falling aircraft or missile were to penetrate a storage tank or pipeline and cause a fire, the damage could be extensive. However, the probability of an airplane crash into a plant has been estimated to be approximately 2.5 x 10^{-4}.[7] The probability of a mis-fired missile or debris from an exploding missile hitting a plant or a pipeline is less than one in 10 billion.[7] Although these estimates are highly site specific, these events do not appear to present significant hazards to energy industry installations.

12.2.2 Sabotage and Terrorism

No industrial installation is immune to sabotage. Sabotage may be performed by enemy agents, by dissident groups, by disgruntled employees, or by individuals who are mentally unstable.[148] Figures on the prevalence of sabotage are not available. Much of the data is classified. It is also possible that some cases of sabotage are not recognized but are treated as accidents, and that other cases are recognized but not reported.

It is impossible to determine the total amount of damage due to sabotage. Until the 1960's, this nation was relatively free of civil disorder. Violence as an expression of group dissatisfaction was not the norm. Since the mid 1960's, however, sabotage and terrorist activities have increased. The use of bombs and incendiary devices has multiplied. It is now estimated that there are approximately 2000 bombing incidents per year, resulting in 20 to 25 deaths, and 170 to 180 injuries. Generally the bombings are politically motivated, with political targets such as government installations. Often the bombings have been directed at "Big Business", especially banks. The energy industries have not been a frequent target. Out of approximately ninety violent acts which occurred during 1965-1975, only two had energy installations as a target.[151] There is, however, no way of predicting what future damage will be the result of sabotage and terrorism.

Industry experts feel that industrial sabotage and arson is not an infrequent occurrence. Generally, the individual acts result in only minor economic damage and are regarded more as an irritant than a danger. Most industrial sabotage is done by disgruntled employees. Acts of industrial sabotage frequently occur during strikes. For example, delivery vehicles to and from an installation are waylayed and damaged or destroyed. Communication lines and power lines may be cut. Some industrial sabotage is done only to prolong the duration of an activity, so that the workers are able to stay on the job and get paid for a longer period of time. The improper welding found on sections of the Alaska pipeline, currently under construction, may fall into this category.

The petroleum, gas, and power industries are important, visible, and easily accessed targets of potential sabotage. The following is a list of particularly vulnerable aspects of these industries:

1. Many oil and gas wells are clustered on relatively small offshore platforms.

2. Often oil and gas storage tanks are next to producing equipment.

3. The production of many wells is funneled into a few pipelines.

4. Pipeline pumping stations are above ground, unmanned, unguarded, and often located in remote areas. Pipelines are a tempting target for the saboteur, since he can cuase not only the loss of oil or gas but also an extensive fire. It has been stated that a trained group of a few hundred persons knowledgeable as to the location of major pipelines and control stations and with destruction in mind, could starve our refineries from crude or cut off

most of the natural gas.[10] In the gas distribution system, the major point of vulnerability is the "city gate", where the regulators, meters, and points of odorization are located.[145]

5. Many of the control of operations at the wells and at the refineries is done by computer. Often control of several operations is located in one control room. These control rooms often have little or no security. Computers are easily tampered with using magnets or other means of destroying their data banks stored on magnetic disks or tapes. Knowledgeable personnel may incorporate changes into the computer programs which could cause millions of dollars of damage.

6. The petroleum and gas industries are heavily dependent upon the availability of electric power. Approximately 50% of total crude production is dependent upon electric power. A serious power outage could bring a major refinery to a halt.

The power industry is most vulnerable at major switching stations. These are above ground, unguarded, and easily accessible. The transmission lines themselves are also vulnerable. The power industry is dependent upon oil, gas, and coal for the generation of electricity. Thus, the interdependence of these energy industries is one of their most vulnerable aspects.

12.2.3 War

It is unlikely that a conventional war will be fought in this country. Therefore, vulnerability of energy installations to war means vulnerability to nuclear war.

The effects of a nuclear weapon are as follows:

1. The nuclear explosion is an extremely powerful detonation. Shock waves and tremors will be felt for many miles. Secondary earthquakes may be initiated.

2. A large portion of the energy of a nuclear explosion is emitted in the form of light and heat. This is capable of causing skin burns and starting fires.

3. An electromagnetic pulse, sometimes called radioflash, is produced which can damage electrical or electronic equipment in the area.

4. Radioactive earth and other materials are drawn up into the atmosphere. These radioactive particles then fall back to earth over a period of time and cover a wide area. This is called "fallout". The full range of effects from fallout are often not apparent till months or years later, when the radioactive materials have entered the natural food cycle and show up in vegetable and animal products, and, ultimately, in the human body.

There are no data available on the likelihood of a nuclear attack. However, the Office of Emergency Preparedness has developed the following profile of a "typical" attack:

1. The attack will last 48 hours and consist of 450 weapons representing a total yield of 2,300 megatons.
2. Most of the weapons will fall during the first hours.
3. Explosions will be evenly divided between air and ground bursts.
4. Nuclear devices will be directed at military, industrial and population centers.
5. Ports and transportation centers will be especially hard hit.
6. Fallout will be a serious problem, but most parts of the country will be accessible within two weeks. No major section of the country will be completely isolated due to fallout. Fallout intensities at one hour past the beginning of the attack will exceed 10,000 roentgens per hour in a few cases. However, many areas will receive less than 100 roentgens per hour.

Such an attack would reduce the population of the United States from 200 million to 145 million. During the first month, 31 million would require hospitalization. Deaths during the first year would further reduce the total population to 125 million, giving a total decrease of 38%.[144] (The population figures given here are all based on 1970 statistics).

The damage created by a 20 megaton blast would be as follows.[144]

1. At impact site:

   A 0.66 mile diameter crater will be produced. The fireball will have a diameter of 2.9 miles.

2. Within 5 miles of impact:

   The destruction will be essentially total. Ninety-eight percent of the population will die.

3. 5 to 7 miles from impact:

   Damage will be heavy, 40% of population will die, another 25% will be injured.

4. 7 to 11 miles from impact:

   Damage will be moderate. Five percent of population will die, 20% will be injured.

5. 11 to 15 miles from impact:

Damage will be light, 10% of population will be injured.

6. More than 15 miles from impact:

There will be no direct damage or injury. Fallout will be the only danger.

The primary targets for nuclear explosions will be major government, military, and industrial installations. This implies that the North East Corridor, the California Coast line, and the large industrial complexes clustered around Chicago will be attacked. Due to their wide geographic distribution, oil and gas wells are less vulnerable than refineries and processing plants which tend to be clustered in a few major areas. The power system is particularly vulnerable. The elimination of a few of the major nodes in the power transmission network could cause loss of power over a large area, such as the entire Northeast.

12.3 Precautionary Measures

The destructive aspects of natural disasters may roughly be grouped into the categories of excessive wind, flooding, and earth movement. In addition, due to the flammability of natural gas and many petroleum products, explosions and fires are a constant danger.

The best defenses against disasters are to design and build facilities which stand a chance of withstanding the destructive forces, and to be aware of whatever advanced warnings are available, and to take appropriate action.

The effect of the man-caused disasters of sabotage and war are similar to those caused by natural disasters. Their severity varies, however, from slight to the point of total annihilation.

1. Structural Safety Aspects - Careful planning goes into the design of any major industrial installation. Among the many design criteria, safety factors have great importance. It is customary, for example, to design a structure to withstand the worst 100 year or 200 year storms. In hurricane or tornado-prone areas, this means designing for wind forces in excess of 200 miles per hour. For example, storage tanks must be able to withstand impacts from debris swept up by such winds. If flooding is a danger, low-lying processing and storage facilities are either avoided, or are constructed appropriately. The siting of a major installation is generally studied with great care. Clearly, construction on top of a known seismic fault is to be avoided. In certain parts of the country, faults are quite prevalent, and some structures such as pipelines must cross over them. Pipeline construction now includes several techniques that ensure that the lines can "give" (at least to some degree) when subjected to pressure due to earth movement.

Careful consideration is also given to duplication of function or backup facilities. For example, some degree of manual control for the operation of the facilities must be provided, should the controlling computer be destroyed or become disabled (all modern petroleum processing plants are operating with computer control). Alternate sources of electric power are generally included in the plans. Power lines are, unfortunately, among the most vulnerable components of the total energy systems.

Finally, specific "safety" areas are included in the design. These areas may serve as a refuge for employees and as a repository of valuable company documents. The design safety factors of these areas are several times those used in the rest of the installation. Presumably they are able to withstand moderate explosions and fires and provide protection from radioactive fallout.

2. Immediate Protective Measures - Most natural disasters, as well as nuclear attack, are preceded by some advance warning. The Federal Government has instituted a Natural Disaster Warning System. Notice of impending hurricanes, tornadoes and floods is given generally hours before the expected event. Some research is now being done to also develop earthquake warning systems.

Regardless of the amount of advance warning, the best protective measure for any installation is a well-conceived and exercised Emergency Plan. Such a plan should be put into effect as soon as a major emergency becomes apparent. The Petroleum and Gas Industries have spent considerable effort on the development of emergency plans. The following specific points are taken from the emergency planning guidelines relating to nuclear attack, as promulgated by the Office of Civil Defense. They are applicable to any major emergency situation. Actions to be taken are:

1. Establish areas of relative safety for all personnel.
2. Ensure continuity of management.
3. Coordinate mutual aid with federal, local and state agencies, fire and police departments, other installations, local utilities, etc.
4. Establish methods of communication.
5. Arrange emergency staffing of vital jobs such as repair crews.
6. Establish evacuation and shut-down procedures.
7. Arrange for emergency power supply.
8. Establish plant security procedures.
9. Establish fire control procedures.
10. Protect vital records.
11. Obtain emergency supplies.[144]

APPENDIX I

AGENCIES AND ORGANIZATIONS CONTACTED

GOVERNMENT

Bureau of Labor Statistics

Bureau of Mines

Bureau of Reclamation

California Assembly - Office of Research

California State Energy Commission

City of Oxnard Planning Commission

Defense Civil Preparedness Agency

Energy Research and Development Administration

Environmental Protection Agency

Federal Energy Administration

Federal Power Commission

Federal Highway Administration

Federal Railroad Administration

Mining Enforcement and Safety Administration

National Highway Traffic Safety Administration

National Transportation Safety Board

New York State Public Service Commission

Occupational Safety and Health Administration

Office of Pipeline Safety Operations

Office of Safety Programs - Department of Transportation

GOVERNMENT (continued)

- Senator Barry Goldwater's Office
- United States Coast Guard
- United States Senate Committee on Interior and Insular Affairs
- United States Senate Internal Security Committee

INDUSTRIAL AND COMMERCIAL FIRMS

- Advanced Systems Laboratory, AMF, Inc.
- Booz, Allen and Hamilton
- Oil and Gas Consultants International
- Petty-Ray Geophysical, Inc.
- Scientific Applications, Incorporated
- Seismograph Service Corporation
- Standard Oil of California

INSURANCE COMPANIES

- American Insurance Association
- Industrial Research Insurance Company
- Insurance Information Institute
- Insurance Institute of America
- Oil Insurance Association

MISCELLANEOUS

- Air Pollution Control Association
- American Academy of Environmental Engineers
- American Institute of Mining Engineers
- American Water Works Association
- Chemical and Engineering News

MISCELLANEOUS (continued)

- Denver Research Institute
- Institute for Disaster Research - Texas Institute of Technology
- National Academy of Sciences
- Society of Exploration Geophysicists
- Society of Petroleum Engineers of AIME
- Texas Petroleum Research Committee
- Water Pollution Control Association

TRADE ASSOCIATIONS

- American Boiler Manufacturers Association
- American Gas Association
- American Institute of Mining, Metallurgical, and Petroleum Engineers
- American Petroleum Institute
- American Petroleum Refiners Associations
- Association of Oil Pipelines
- Bituminous Coal Association
- Edison Electric Institute
- Electric Power Research Institute
- Independent Petroleum Association of America
- Independent Refiners Association of America
- Independent Refiners Association of California
- Independent Terminal Operators Association
- Institute of Gas Technology
- Mid Continental Oil and Gas Association
- National Coal Association
- National Fire Protection Association

TRADE ASSOCIATIONS (continued)

- National Gas Supply Committee
- National Oil Jobbers Council
- National Petroleum Council
- National Petroleum Refiners Association
- National Safety Council
- Petroleum Equipment Institute

UNIONS

- International Oil, Chemical, and Atomic Workers Union
- International Union of Petroleum Workers
- United Mine Workers of America

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